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Future Astronomical Observatories on the Moon

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PROLOG

On January 10, 1986, nearly 100 astronomers, space scientists, physicists, and engineers gathered at the Shamrock Hilton Hotel in Houston, Texas, to consider the topic, "Astronomical Observations from a Lunar Base." The challenge presented to the 20 speakers was to consider the impact of a manned lunar base some 15 to 30 years in the future on their branches of astronomy. Since many of the participants had no prior experience in space-based observations, it was hoped that an unbiased view of the future directions and relative merits of lunar-based astronomy could be obtained. The result of our crystal ball gazing was a remarkable consensus among the participants. Simply stated, we conclude that the Moon is very possibly the best location within the inner solar system from which to perform front-line astronomical research.

This bold contention is based upon a recognition that the Moon offers some important advantages compared to Earth-surface or Earth-orbit locations for observations in each part of the electromagnetic spectrum. These advantages include a very clean, very high vacuum (10^{-12} torr) environment, a high-stability platform with low seismicity (10^{-6} times Earth), low radiation background, natural cryogenic surroundings (<70 K at the poles), large areas with natural landforms (i.e., impact craters), 14-day nights, reduced gravity (one-sixth that of Earth), proximity to and easy accessibility from scientific stations, and availability of raw materials for construction. As a result, we are presented with opportunities for significant expansion of traditional astronomical instrumentation and observations, as well as with opportunities to pioneer new techniques and to open new wavelength windows. Included among the expansion of currently existing technologies are large-area detectors in high-energy x-ray and gamma-ray astronomy and in cosmic-ray and neutrino physics; "naked," large-format cathode arrays in the passive-cooling environment of the lunar surface at infrared wavelengths; Arecibo-style radio antennas within lunar craters; and very-long- and ultra-long-baseline radio interferometry on the Moon and between the Earth and the Moon. Among the exciting new techniques is the possibility of phase-coherent optical interferometry producing resolutions that are 100 000 times better than those of existing ground-based telescopes and 10 000 times better than that of the Hubble Space Telescope. One of the last remaining, unexplored wavebands at very low frequencies (i.e., a few megahertz) will be opened for observations with simple dipole arrays on the lunar far side. A summary of the instrumentation and resulting astronomical science from a lunar base is presented in table I.

We recognized at the beginning of this workshop that astronomy will not be the prime motivating force in establishing a permanent lunar base. Other political or possibly military factors, international competition, and the human desire for exploration of our environment will likely drive the timetable for establishment of a Moon colony. However, many of the workshop participants view as inevitable the building of a lunar base by the beginning of the 21st century. Since astronomy will not be the prime mover, our science also will not have to bear the major expense in constructing a base. Thus, although we are aware of the potential drain of resources and funding as a result of manned versus unmanned exploration (ref. 1), we also view a lunar base as a significant opportunity to advance astronomy by piggybacking on a facility constructed with national (or international) funds and support. One of the results of this workshop was a demonstration that the Moon holds great promise for astronomy. Therefore, we wish to make it known to the planners of a future lunar colony that a scientific preserve for astronomy should be considered in conjunction and in cooperation with geology, mining, manufacturing, and transportation facilities on the Moon.

Both the Field Committee report, "Astronomy and Astrophysics for the 1980's" (ref. 2), and the recently released report of the National Commission on Space (ref. 3) have advocated the establishment of a scientific base on the Moon in recognition of the unique opportunities that it affords. Observations on the Moon represent a logical extension of the national observatories on Earth and the first-generation low Earth orbit observatories such as the High-Energy Astronomy Observatory (HEAO) series and the Infrared Astronomy Satellite (IRAS). Future progress in the so-called "great space observatory" series will include the Hubble Space Telescope and the Gamma-Ray Observatory, and, hopefully, an Advanced X-Ray Astrophysics Facility (AXAF) and a Space Infrared Telescope Facility (SIRTF). The proposed NASA Space Station will present opportunities for relatively inexpensive astronomical experiments serviced by a human crew. The next-generation astronomical observatories on the Moon will extend the great space observatory series to our nearest neighbor in the solar system. With these facilities, we may approach the goals set by the Space Sciences Board and the National Commission on Space aimed at "understanding the evolutionary processes in the Universe that led to its present characteristics . . . and using our new understanding to forecast future phenomena quantitatively, particularly those that affect or are affected by human activity" (ref. 3).

ACKNOWLEDGMENTS

This workshop and these proceedings would not have been possible without the generous support of Mike Duke and Barney Roberts from the NASA Lyndon B. Johnson Space Center and of P. W. Keaton from the Los Alamos National Laboratory. We hope that this report will aid NASA in its long-range planning activities for the new century.

I would like to thank members of the organizing committee including Wendell Mendell and Harlan Smith for their help in assembling the speakers and the program for this workshop. Their words of inspiration at the beginning of the workshop set a positive tone and helped to guide our forecasts for astronomy from the Moon. I am also grateful to David Clarke for helping to assemble the workshop mailings and for his assistance during the workshop sessions. A most important word of thanks goes to all the speakers at the workshop for their efforts in sharing their visions of the future with us.

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August 1986

REFERENCES

1. Van Allen, James A.: Space Science, Space Technology, and the Space Station. Scientific American, vol. 254, 1986, pp. 32-39.

2. Astronomy and Astrophysics for the 1980's. Report of the Astronomy Survey Committee, Vol. 1, National Academy Press, 1982, pp. 165-166.

3. Pioneering the Space Frontier. The Report of the National Commission on Space, Bantam Books (New York, N.Y.), 1986, pp. 25-57.

TABLE I.- SUMMARY OF FUTURE ASTRONOMICAL OBSERVATORIES ON THE MOON

Telescope	Lunar advantages	Scientific goals
X-RAY AND GAMMA-RAY	No atmospheric absorption. Large collecting area, high throughput. High resolution via long focal lengths.	Cosmology: Clusters of galaxies in formation. X-ray background. Bursting sources: Black holes. Supernova nucleosynthesis. Direct emission from accretion disks of black holes.
OPTICAL		
A. Large apertures (15 to 20 m)	Diffraction-limited imagery with high sensitivity. Use glass mined on the Moon.	Galaxies in formation. Distant quasars. Expansion and evolution of the universe.
B. Optical interferometer	Phase-coherent interferometry. Very high resolution: 10 μarcsec for 10-km baseline at 500 nm. 100 000 times better than ground-based. 10 000 times better than Hubble Space Telescope.	Detect planets around other stars. Study sunspots and flares on other stars. Resolve optically violent variables. Resolve cores of elliptical galaxies.
INFRARED	No atmospheric absorption. Excellent vacuum. Passive thermal shielding. "Naked" cathode arrays.	Probe center of Milky Way. Direct examination of star formation. Study planets in formation.

TABLE I.- Concluded

Telescope	Lunar advantages	Scientific goals
RADIO		
A. Arecibo-style antennas	Low gravity. Natural shaping in craters. High sensitivity to extended radio emission. Simple observations.	Radar measurements of planets and asteroids. Sensitive HI and continuum mapping of gas in Milky Way. Study solar wind/magnetosphere for integrated view.
B. Lunar very large array (VLA) or very-long-baseline array (VLBA)	High phase stability. Stable baselines. Lunar materials for construction.	High-accuracy astrometry. Short spacings for longer baseline interferometers.
C. Moon-Earth radio interferometer	Very high resolution: 12 μarcsec at 10 GHz. 0.4 μarcsec at 300 GHz.	Determination of Hubble constant using statistical parallax of extragalactic masers. Mapping the "engines" at the cores of active galaxies and quasars.
D. Very low frequency array	Lunar far side provides natural insulation from manmade radio static. Opening new window to the universe.	Evolution of extragalactic radio sources. Measure nonthermal emission from stars. Study low-energy population of energetic particles in planets, pulsars, active galaxies.
E. Millimeter-wave array	No atmosphere attenuation. High resolution.	Mapping new star formation regions in other galaxies.
COSMIC-RAY AND NEUTRINO TELESCOPES	New window of energies. Low radiation background. Weak magnetic field. Large-volume detectors.	Distribution of primaries. Monitor radiation exposure for humans. Very-high-energy cosmic rays and neutrinos. Solar flare production and solar nucleosynthesis.

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PART I

REASONS FOR PERFORMING ASTRONOMY ON THE MOON

One question that figured prominently in the minds of the participants at the Lunar Base Workshop was, "Are there truly significant scientific reasons for performing astronomy on the Moon as opposed to performing ground-based and low Earth orbit observations?" This question was perceived as a key issue, especially in light of the expected cost of a permanently staffed lunar base. Therefore, the first portion of the workshop was devoted to a discussion of the advantages and opportunities afforded by the Moon for astronomy, the cost of a lunar base with proper long-range planning, and a bit of philosophizing on future directions for astronomical instrumentation.

In part I of these proceedings, W. W. Mendell begins by considering the potential function of astronomy in planning for a lunar base during the early 21st century. Mendell has been one of the leading advocates for a permanent settlement on the Moon and has given considerable thought to the possible impact of such a station on science. P. W. Keaton follows with a paper demonstrating that a lunar base is affordable at a yearly cost less than that of the Apollo Program if long-range planning begins now. Keaton's predictions for future growth of the U.S. gross national product (GNP), needed to create the funding environment for a lunar base, are considered to be conservative by many economists. The third paper in this series is by a leading lunar geologist, G. J. Taylor. Taylor describes the geological features of the Moon that may be advantageous for astronomical observations. In the same vein, J. D. Burke presents a paper noting that some permanently shadowed regions on the Moon could provide natural passive-cooling environments for astronomical detectors. The final paper in part I by H. J. Smith was considered by many workshop participants to be the highlight of the day. Smith carefully and methodically weighs the opportunities along with the potential advantages and disadvantages of the Moon for astronomical observatories. Taking an unbiased approach, he concludes that lunar observatories will clearly be a major factor in the future of astronomy in the next century.

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SCIENCE OBJECTIVES IN THE LUNAR BASE ADVOCACY

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Rationale for a Lunar Base

As we approach the 21st century, the U.S. manned space program will focus on the operation and evolution of low Earth orbit (LEO) space stations and the development of orbital transfer vehicles (OTV's). From that time forward, manned space activities will consist no longer of simple orbital sorties; permanent presence on station will be an intrinsic element of new programs.

The deployment of reusable upper stages (OTV's) at the LEO station will have enormous significance. Within the context of the Space Transportation System, the reusable OTV has been seen as a service vehicle for operations in geosynchronous orbit (GEO), which lies at the very edge of the Earth's gravitational sphere of influence. Designed to escape the Earth's grasp and return, the OTV will allow access to all of cislunar space, including inevitably the surface of the Moon.

We argue that the establishment of a lunar base will become a major space policy issue by the time this transportation element enables routine visits to the Moon. Awareness of the implications of this technology is most likely to occur within the next 10 years, as the manned LEO space station becomes a reality. In anticipation of a future public debate, scientists, technologists, and policy analysts within and outside NASA have been devoting some thought to the lunar base issue. A well-studied base of information will be critical to the success of the decision process.

As a first step, we have made technical and budgetary projections as conservatively as possible, and the results appear to confirm the feasibility of establishing a permanently manned lunar base by the first decade of the 21st century. However, the scale of project envisioned would require a long-term commitment. From the experience with the Apollo Program, we learn that the political process will not continue support without a clear payback in terms of the economy, of social goals, or of national security. Viability of continuous lunar surface operations over the long term will depend on attainment of a high degree of self-sufficiency in space and therefore on the exploitation of any economic potential for the use of lunar resources. Consequently, we tend to focus on strategies which maximize use of local materials and the local environment to minimize the high transportation costs associated with imports from the Earth.

Research on the Moon

The success of planetary surface operations such as mining, surface transportation, construction, and industrial processing will depend on the adaptation of technologies to the lunar environment. Thus, we anticipate that a significant fraction of the man-hours spent on the surface in early missions will be devoted to applied research. The scope of the exploratory experimentation could range from geological surveys of potential lunar resources to studies of the effects of reduced gravity on chemical engineering designs to measurements of surface properties appropriate to civil engineering.

Although learning to function in the lunar environment will be a major task for early selenauts, a lunar base program must include important basic research as a high-priority activity.

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Advancement of human understanding of the physical world accompanies the opening of any new frontier.

Defining Science Objectives

Definition of potential scientific experiments is important to NASA planners, who must consider the necessary equipment and operational requirements imposed by the investigations. Conversely, scientists need to seek out opportunities to participate in planning. A failure to do so means that engineering and technological goals preempt resources which could be used for research.

Since lunar base planning has not been a NASA activity with high visibility or significant financial support, there has been a problem getting inputs from a representative cross section of the scientific community. The exception has been lunar and planetary science, which has an intimate connection with NASA. For the most part, scientists are unaware of the problem or consider the scenario to be excessively speculative and remote or have little knowledge of the lunar environment and its potential advantages to scientific investigations.

Those involved in lunar base planning have tried to bring scientists of diverse backgrounds together in workshops or symposia to discuss possible experiments uniquely suited to the Moon or unusually enhanced by being performed in the lunar environment. However, the financial resources for sponsoring such meetings are very limited. One successful communication mechanism is the convening of special sessions, such as this one, at professional meetings. In general, the sessions are conceived, organized, and advertised by interested professionals. The meetings not only communicate the potential opportunities for science in future space projects but also bring together researchers of similar backgrounds for good, old-fashioned brainstorming. Out of such gatherings can come excellent ideas for innovative experiments in the space environment.

For the lunar base, we are most interested in basic research which can be done only on the Moon or can be done best there. Once humans live on the Moon, many experiments will be done simply because it is convenient. However, in preparing for a decision on whether to embark on a Moon base, we must determine the major advances in knowledge and understanding that would be enabled by the enterprise. Although science is rarely the sole justification for major public policy decisions, it is always a full partner to exploration; thus, it is important to be sure that the scientific rewards of the endeavor are fully understood and exploited.

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CAN THE UNITED STATES AFFORD A LUNAR BASE?[1]

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Introduction

Establishing a lunar base will require steady funding for a decade or two. The question addressed here is whether such a large space project is affordable at this time. The relevant facts and methodology are presented so that the reader may formulate independent answers. We show that a permanent lunar base can be financed without increasing NASA's historical budgetary trends.

Costs of placing a permanent base housing 24 people on the Moon were estimated in a 1968 Stanford University and NASA Ames Research Center study (ref. 3). The group concluded that over a 15-year period, the total development, acquisition, delivery, and building costs would be $17.4 billion, which translates to $58 billion in 1985. A 1984 investigation by Scientific Applications, Inc., estimated a $16-billion cost for a temporary manned reconnaissance outpost on the Moon (ref. 4). And a NASA Lyndon B. Johnson Space Center team (ref. 5) has estimated that it would cost between $80 billion and $90 billion to place a permanent base on the Moon. The NASA team emphasized base self-sufficiency and assumed that the lunar base project would require 25 years to complete.

As a comparison, the Apollo Program was completed in 11 years and cost about $85 billion (in 1985 dollars), during a period in which the U.S. gross national product (GNP) was less than one-half the current level. Thus, a $90-billion lunar base project requiring 22 years to complete would have less than one-fourth the annual impact on the U.S. economy as did the Apollo Program during the 1960's. Assuming that a permanent lunar base will cost less than $100 billion, we turn now to the question of whether the United States can afford such a cost. First, we consider the historical trends of the U.S. GNP.

U.S. Economic Trends

During the past 22 years, the United States has accumulated more national income than it did in all its previous history. After correcting for inflation, we find that the gross national product has increased at an average rate of 3.2% per year despite all the globally and nationally significant events affecting the growth rate in one way or another during the last 100 years.

Taking GNP data from the Department of Commerce (refs. 6 and 7) and implicit price deflation numbers from the Office of Management and Budget (OMB) (ref. 8), we show in figure 1 a plot of U.S. GNP in 1985 dollars for the years 1889 through 1984. In addition, 1985 projections of the Congressional Budget Office (CBO) (ref. 9) indicate that the growth trend is expected to continue through 1990 and beyond.

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[1] This paper was adapted from references 1 and 2.

The most striking feature of the GNP data curve is its close fit to a single exponentially rising function ae^{bt}, where t is the time in years and a and b are adjustable parameters. Making a least-squares fit to the actual constant dollar data, we determine that $b = 0.032$, which is the average annual growth rate of the GNP since the year 1889.

The exponential function of figure 1 exhibits a doubling time of 21.7 years. Hence, in recent decades, the total real income of the Nation has roughly doubled every generation, whereas the population has increased by less than 30%. One doubling time is adopted here as a natural unit of time to use for a long-range view of the U.S. economy.

U.S. Federal Budget Trends

To devise a rationale for projecting long-range U.S. expenditures for a national space program, we note that all Federal space funds, like other Government funds, are under constant and conflicting pressures from various segments of the public: military agencies, the private sector, scientific and engineering communities, and political coalitions. We assume that space program supporters will continue to fight for, and to receive, the same fraction of their category of funding source that they have fought for, and received, in the past. For our purposes, those funding sources must be identified in categories that are narrow enough to enable us to distinguish among past budget trends and broad enough to allow room for the statistical "give and take" of the budget process averaged over many years and several political administrations. To accomplish this objective, we observe that for the past 30 years, space activities have been funded mainly by NASA and the Department of Defense (DOD), and we identify the pools of Federal money that supply their funds.

The U.S. Federal budget constitutes less than 25% of the Nation's GNP. Figure 2 shows a 27-year distribution of Federal Government spending as separated into categories of national security, social welfare, and "other." These are categories that can be traced through the documents of the U.S. Department of Commerce (refs. 6 and 7). Civilian space programs are funded mostly through NASA from the "other" category, which has remained more or less a constant fraction of the GNP as shown in figure 2. To compare, we observe that military space programs come from the national security category, which remained at a roughly constant dollar budget from about 1960 to 1982.

Thus, if we were projecting both military and civilian space programs, we would use a combination of these two trends — constant dollar and constant fraction of GNP — as guidelines for extrapolating Government expenditures on space activities into the future (ref. 1). Here, however, we will restrict ourselves mainly to the NASA budget and make a constant-fraction-of-GNP extrapolation. First, however, we need to determine the length of time in the future that past and present trends can reasonably be expected to last.

How Long Will Economic Trends Continue?

We can think of the GNP as the sum of a large, exponentially rising component ae^{bt}, with a characteristic time of $1/b$, and a small modifying term that averages to zero and accounts for major events such as a worldwide depression or a world war. The average growth rate is then the sum of a statistically significant number of random and uncorrelated events $b_i(t)$, such as the invention of the transistor (positive) and the influx of Japanese cars to the U.S. market (negative). The growth rate may be written as a sum of the individual events, $b = \Sigma\, b_i(t)$, for which the least-squares search shows that, on the average, b has been a constant over the past 97 years even though the components $b_i(t)$ have not been constant. By analogy with physical systems, we hypothesize that b cannot change rapidly over a period of time $1/b = 31$ years. This hypothesis is consistent with the observation that the value of b depends on many random events.

It is easy to show that if the average GNP growth rate changes slowly over 31 years, then the cumulative GNP is relatively insensitive to the growth rate changes. For example, if we represent b by a function starting at 0.032, which decreases linearly with time to 0.0 in 31 years, we find that the projected cumulative GNP over the next 22 years will decrease from the constant b projection by only 10%. As for the value of b, it is interesting that Merrill Lynch projects a 3.1% annual growth rate in real GNP for the period of 1983-93 (ref. 10). The 1984 World Bank projection indicates that the industrial nations' economies (of which the U.S. economy is by far the largest) will have a growth rate for 1985-95 of 2.5%/yr to 4.3%/yr (ref. 11). And an extensive study by the International Institute for Applied Systems Analysis (ref. 12) shows a combined economic growth rate for the United States and Canada of 2.0%/yr to 3.3%/yr for 1985-2000 and 1.1%/yr to 2.4%/yr for 2000-2015. It seems, then, that diverse approaches are consistent with a U.S. GNP growth rate in the neighborhood of 3.0%/yr. Once that rate is accepted as reasonable, the current analysis is relatively insensitive to slow variations from 3.0% growth rates in the future.

We turn now to the question of projecting future U.S. expenditures on civilian space programs.

Future Civilian Space Funding

The actual U.S. GNP in fiscal year 1985 was $3937 billion (ref. 13). Starting with 1985 as year zero, we can integrate the exponential curve to show that, at a 3.2%/yr growth rate, the cumulative GNP will be $123 000 billion (in 1985 dollars) during the 22 years from the end of 1985 through 2007. We agree, as discussed earlier, to put a 10% uncertainty on this number to account for the large uncertainty in the future growth rate b.

Figure 3 shows that, historically, about 0.5% of the U.S. GNP has been spent for all space activities, with about 0.34% going to NASA. Alternatively, NASA's budget outlays in fiscal year 1985 (FY85) were $7.3 billion (ref. 14) or 0.18% of the 1985 GNP. Assuming that the NASA budget continues to grow – along with the "other" budget category in figure 2 – at a constant percentage of the GNP, we can anticipate that NASA's cumulative budget for 1986 through 2008 will be $220 billion to $420 billion, depending on whether we take 0.18% or 0.34% of the cumulative GNP.

Of the 0.34% of GNP historically spent on civilian space activities, about one-half can be attributed to large "discretionary" acquisitions (the Apollo and Space Shuttle Programs) and the other one-half can be attributed to space science and technology, aeronautics, overhead, etc. We therefore deduce that during the next 22 years, the United States will spend between $110 billion (1/2 × 0.0018 × $123 000 billion) and $210 billion (1/2 × 0.0034 ×$123 000 billion) on large, discretionary space projects such as a space station, a lunar base, or manned Mars missions.

Although $110 billion is more than enough to build both a space station and a lunar base in the next 22 years, we should not adopt this figure as a lower limit without further thought. A corollary to our earlier hypothesis (that economic trends cannot change quickly in a time $1/b$) is that a trend is not validated until it has persisted for a time $1/b$. To give excessive weight to the NASA budget history in the 1970's would be inconsistent. If we adopt the procedure of giving twice as much weight to NASA's budget for the last 15 years as we give to that for the first 15 years, then we find that 0.24% (instead of 0.18% or 0.34%) is the predicted trend for the future NASA budget as a fraction of GNP. One-half of this figure comes to 0.12%, or $150 billion, to be spent on large space projects over one GNP-doubling time. In light of these observations, it seems safe to assume that a lower limit of 0.1% of the U.S. GNP will be spent on large space projects over the next 22 years. This percentage comes to $120 billion in 1985 dollars.

Concluding Remarks

When we are projecting costs, past experience often proves a better guide to future actions than predictions based on "first principles." We have observed that the average growth rate of the U.S. GNP has varied very little from 3.2%/yr during nearly a century and that the growth rate consists of a statistical average of many uncorrelated phenomena. These observations suggest the hypothesis that the average growth rate will change slowly during a period of approximately 31 years. We deduce from this hypothesis that economic trends that have lasted for three decades will change only slowly over the next three decades. Our results are obtained from a consistent application of these concepts. Our results agree with other current forecasts.

An affordable space program may be defined as one not so large as to keep the GNP per capita from increasing. In that sense, an amount 5 times any of the alternatives discussed here would be affordable. In other words, the United States can afford a much larger space program than any mentioned herein.

Over the long term, the U.S. economy is robust. Barring unforeseen and unprecedented difficulties, it will generate a GNP of about $123 000 billion during the next 22 years, 0.24% of which is likely to be spent by the Government on civilian space programs. Past patterns of spending suggest that one-half of this $300 billion will be available for major national commitments to large, focused space programs.

Even though the future space budget was deduced using a conservative analysis, $150 billion over 22 years would fund a much larger project than most planners seem willing to suggest publicly. The dangers of not making major long-term commitments now are twofold: an unnecessarily miserly approach to our nation's space program can be a self-fulfilling prophecy, and without a long-range perspective, we run the risk of spending the money unwisely by fits and starts.

References

1. Keaton, Paul W.: Why Billions Can and Should Be Spent on Space. Astronaut. & Aeronaut., May 1983, p. 86.

2. Sellers, Wallace O.; and Keaton, Paul W.: The Budgetary Feasibility of a Lunar Base. Lunar Bases and Space Activities of the 21st Century, W. W. Mendell, ed., Lunar and Planetary Institute (Houston, Tex.), 1985, p. 711.

3. Moonlab. Stanford-Ames Faculty Workshop in Engineering Systems Design, June 24-Sept. 6, 1968.

4. Friedlander, Alan; Hoffman, Steve; et al.: Manned Lunar, Asteroid, and Mars Missions. A conceptual study conducted by Science Applications International Corporation for the Planetary Society, Pasadena, Calif., Sept. 1984.

5. The Initial Lunar Base and Its Growth Potential (abs.). In papers presented to the Symposium on Lunar Bases and Space Activities of the 21st Century, NASA Lyndon B. Johnson Space Center, Houston, Tex., 1984.

6. Historical Statistics of the United States. U.S. Dept. of Commerce, Bureau of the Census, Washington, D.C., Part 1, 1975, p. 224, tables F1 and F3.

7. Statistical Abstract of the United States: 1981. U.S. Dept. of Commerce, Bureau of the Census, Washington, D.C., 1981, p. 420, table 700.

8. Budget of the United States Government: Fiscal Year 1983. Executive Office of the President, OMB, Washington, D.C., 1982, pp. 2-5.

9. The Economic and Budget Outlook: Fiscal Years 1986-1990. Congressional Budget Office, Report to Congress, 1985.

10. Long Term Outlook: An Annual Review of the Next Ten Years. Merrill Lynch Economics, Inc., Sept. 1983, p. 2.

11. World Development Report 1984. The World Bank, Oxford Press, 1984, p. 35.

12. Hafele, Wolf, program leader: Energy in a Finite World. Ballinger Publishing Co., 1981, p. 134.

13. The Economic Budget Outlook: Fiscal Years 1987-1991. Congressional Budget Office, Report to Congress, 1986, p. 7.

14. Statistical Abstract of the United States: 1986. U.S. Dept. of Commerce, Bureau of the Census, Washington, D.C., 1986, p. 586, table 1019.

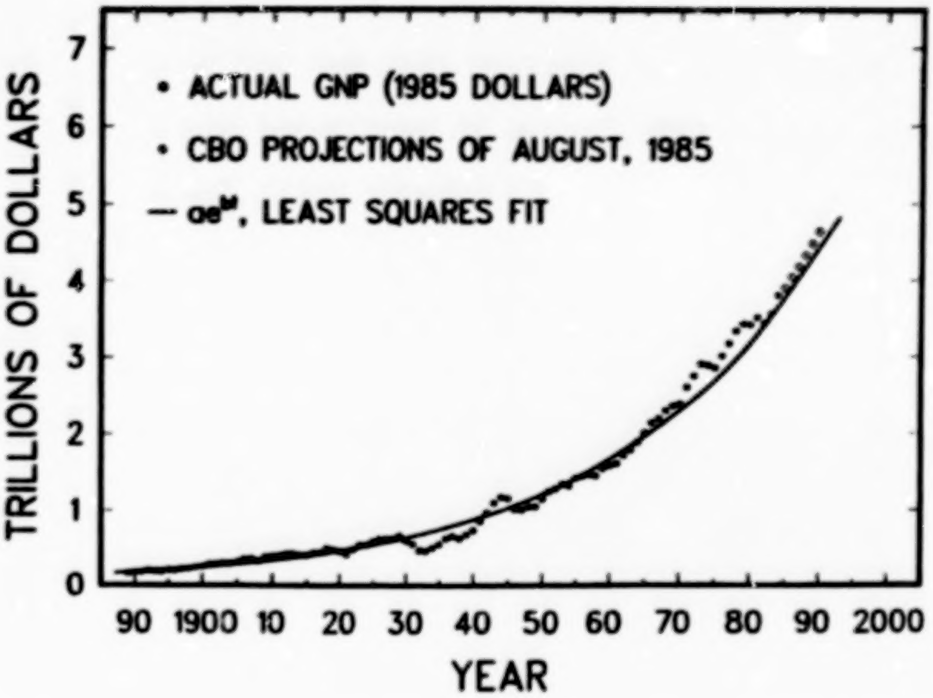

Figure 1.- U.S. gross national product as a function of years.

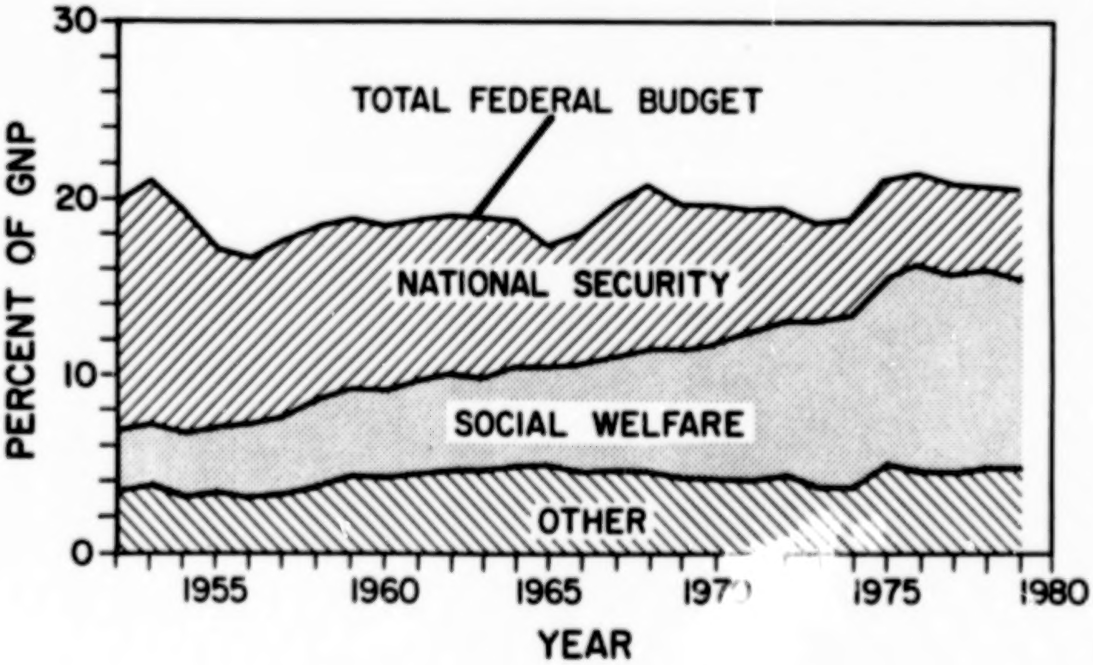

Figure 2.- U.S. Federal expenditures as a fraction of the gross national product.

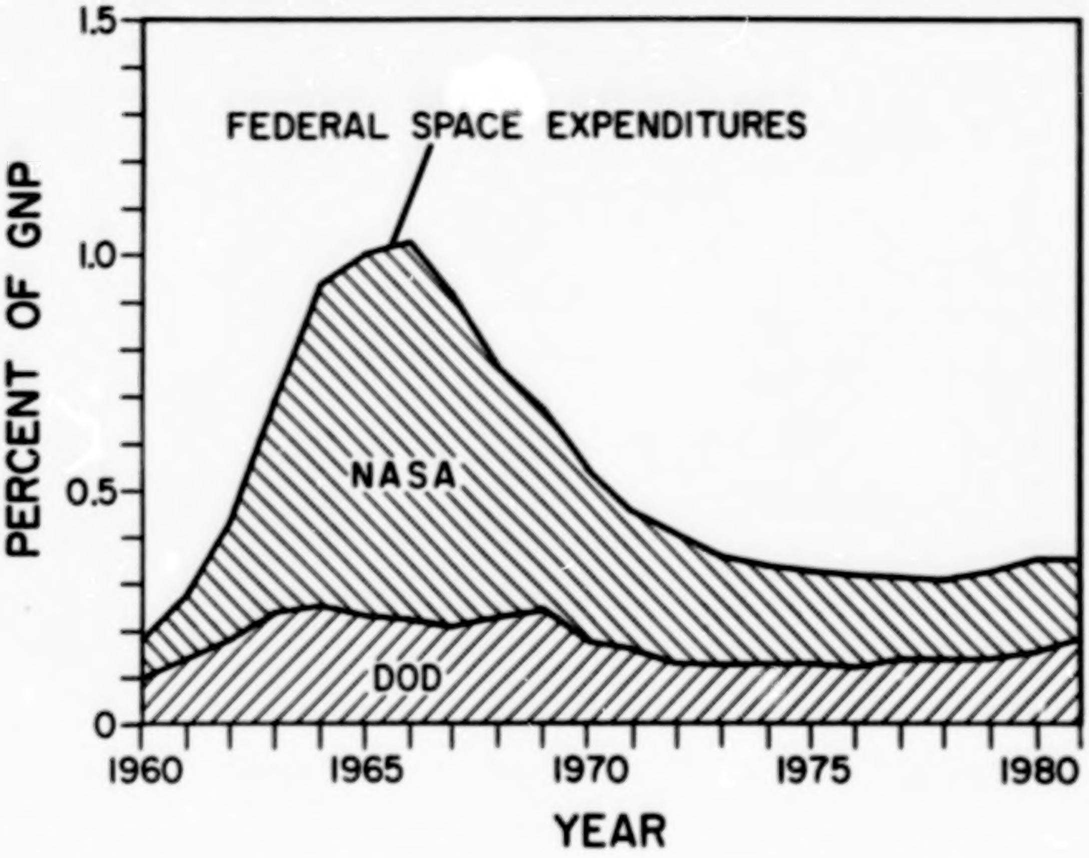

Figure 3.- Federal expenditures on space activities as a fraction of the gross national product.

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GEOLOGICAL CONSIDERATIONS FOR LUNAR TELESCOPES

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Abstract

The Moon's geologic environment has the following features:

1. A gravity field one-sixth that of Earth

2. A synodic rotation period (lunar day) of 29.53 Earth days and a sidereal period of 27.3 Earth days

3. A surface with greater curvature than Earth's surface — A chord along a 60-km baseline would have a bulge of 260 m.

4. A seismically and tidally stable platform on which to build observatories — Total seismic energy released is 2×10^{17} ergs/yr compared to 10^{26} ergs/yr on Earth, and most moonquakes have magnitudes of 1 to 2, within the Earth's background noise.

5. A tenuous atmosphere (i.e., the total mass at night is only 10^4 kg) that allows excellent seeing conditions and does not cause wind-induced stresses and vibrations on structures

6. A large diurnal temperature variation (100 to 385 K in equatorial regions), which telescope facilities must be designed to withstand

7. A weak magnetic field, ranging from 3 to 330×10^{-5} Oe compared to 0.3 Oe on Earth at the Equator

8. A high flux of micrometeorites which, because of the lack of air, are not retarded from cosmic velocity — Data indicate that microcraters 10 μm across will form at the rate of 300/m^2-yr.

9. A regolith 2 to 30 m thick which blankets the entire lunar surface — This layer is fine grained (average grain sizes range from 40 to 268 μm), has a low density (0.8 to 1.0 in the upper few millimeters, rising to 1.5 to 1.8 at depths of 10 to 20 cm), is porous (35% to 45%) and cohesive (0.1 to 1.0 kN/m^2), and has a low thermal diffusivity (0.7 to 1.0×10^{-4} cm^2/sec).

10. A rubbly upper several hundred meters in which intact bedrock is uncommon, especially in the lunar highlands

11. Craters with diameter/depth ratios of 5 if fresh and <15 km across — Larger and eroded craters have diameter/depth ratios >5.

The Moon's geologic environment offers wondrous opportunities for astronomy and presents fascinating challenges for engineers designing telescope facilities on the lunar surface. In this paper, the geologic nature of the stark lunar surface and the Moon's tenuous atmosphere are summarized.

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General Characteristics

The strength of the Moon's gravitational field is one-sixth that of Earth's surface. This property allows use of materials of lower strength than on Earth for structures of equivalent size. Alternatively, much larger structures, such as Arecibo-type radio telescopes tens of kilometers across, can be built on the Moon. As Burke (ref. 1) shows, structural deflection of a 1-m telescope on the Moon would be less than the deflection of a 1-m telescope on Earth by a factor of 100.

The Moon has two physical characteristics that are advantageous for astronomy. One is the slow sidereal rotation period (27 days), which allows long observing times. The other property is the distance between the Moon and the Earth, 384 000 km. This distance provides an extremely long baseline for interferometer systems, using both the Moon and the Earth as locations for elements of the system (e.g., ref. 2).

Because of the Moon's smaller radius, its surface has a larger curvature than does the Earth's surface. For example, a chord along a 10-km baseline would have a bulge of 7.2 m; a 60-km baseline would produce a bulge of 260 m. Designs of large baseline arrays, therefore, need to be based on degree of curvature.

Stable Platform

The Moon provides a stable platform on which to build observatories or other structures. Seismic properties are summarized in table I, which is adapted from reference 3. There are two main categories of lunar seismic signals, based on the depth at which they originate. Almost all occur deep within the Moon at depths of 700 to 1100 km; on average, about 500 deep events were recorded annually during the 8 years of Apollo seismic network operation. These deep moonquakes are related to tidal forces inside the Moon.

Moonquakes also occur at much shallower depths (<200 km), but apparently below the crust (ref. 4). Shallow moonquakes occur much less frequently than do deep moonquakes, only about 5/yr. Shallow moonquakes do not appear to be related to tidal flexing of the Moon or to surface features. For comparison, most earthquakes occur at depths of 50 to 200 km.

Lunar seismic activity is drastically less than terrestrial seismicity (table I). Lunar seismographs detected only 500 moonquakes per year. In contrast, 10 000 detectable earthquakes occur each year. Note that the magnitude of detectable earthquakes is different from that of moonquakes; this difference is attributable mostly to greater seismic noise on Earth. In fact, most moonquakes are the magnitude 1 to 2 range, which is background level on Earth.

The total seismic energy released in the Moon is about 10^8 times less than that released in Earth. The magnitudes of the largest events on the Moon are also much less than those of the largest events on Earth (table I). The most energetic lunar events are the shallow ones, the largest recorded one being only 4.8 magnitude, corresponding to an energy of 2×10^{17} ergs. The largest recorded earthquake measured 9.5 magnitude on the Richter scale, corresponding to an energy of 10^{26} ergs.

Seismic waves are intensely scattered near the lunar surface. This scattering causes the energy of the waves arriving at a given point to be spread out; thus, the damaging effects of a moonquake would be less than those of an earthquake of the same magnitude. (In fact, values of seismic energy and magnitudes reported for the Moon by Goins et al. (ref. 3) are greater than those reported by Lammlein et al. (ref. 5) because the latter authors had not accounted for scattering of seismic waves near the lunar surface or for some instrument effects.) Consequently, it appears that the lunar surface is far more stable than any place on Earth.

The scattering of seismic waves in the Moon is significant down to a depth of 25 km but is most intense in the upper few hundred meters. This intensity implies a lack of coherent layering in this region.

Tidal forces raise and lower the lunar surface about as much as on Earth, where body tides deflect the ground about 10 to 20 cm twice each day. Because the Moon is locked into a synchronous orbit, the main tidal bulge on the Moon is a permanent feature. Nevertheless, small tidal deflections stemming from librations do occur but have much longer periods than on Earth. The tidal flexing of the lunar surface in both horizontal and vertical directions is about 2 mm along the length of a 10-km baseline (Dr. James Williams, personal communication, 1986). The precise amount of motion depends on position on the Moon. Tidal motions must be considered when designing telescope arrays.

Atmosphere

The lunar atmosphere is a collisionless gas. The total nighttime concentration is only 2×10^5 molecules/cm^3 (ref. 6). Its total mass is only 10^4 kg, about the mass of air in a movie theater on Earth at a pressure of 1 bar. This flimsy atmosphere will provide significantly better observing conditions because atmospheric twinkling will be absent. Engineering problems associated with wind also will be absent (ref. 7).

The composition of nighttime lunar atmosphere appears in table II. The gases derive from the solar wind, except for argon-40 (^{40}Ar), which is produced by the decay of potassium-40 (^{40}K) inside the Moon and then diffuses out. Because of instrument limitations, no daytime measurements of gas concentrations were made, but Hodges (ref. 8) calculates that gases of carbon compounds, specifically carbon dioxide (CO_2), carbon monoxide (CO), and methane (CH_4), probably dominate. They are absent at night because of condensation from the atmosphere onto soil particles.

The tenuous lunar atmosphere can be altered significantly by large-scale operations on the Moon. Vondrak (ref. 9) has calculated that if the density of the lunar atmosphere is increased, a point is reached at which rate of gas loss is slowed drastically. This intensification could compromise a number of scientific experiments requiring a hard vacuum, including observations of the solar wind. Considering that each Apollo mission contributed 10^4 kg of gas (ref. 10), temporarily doubling the atmosphere's nighttime mass, it would appear easy to contaminate the Moon's fragile atmosphere when regular flights to and from the lunar surface begin. The atmosphere must be monitored carefully when a lunar base is established. Studying the evolution of the Moon's atmosphere will, in fact, be an interesting research project in itself.

Surface Temperatures

Surface temperatures change drastically from high noon to dawn on the Moon, presenting a challenge to those designing lunar observatories. At the Apollo 17 landing site, for example, the temperature ranged from 384 K to 102 K during the month-long lunar day (ref. 11). Furthermore, the temperature decreases rapidly as sunset approaches, falling about 5 K/hr (fig. 2 of ref. 11). These data apply to equatorial regions only. In polar regions, the predawn temperature is about 80 K (ref. 12). The temperature in permanently shadowed areas at the poles could be lower. The cold nighttime temperature will permit cooling of many types of detectors without use of cryogenics.

The temperature variation is damped out rapidly at depth in the lunar soil (ref. 11). At a depth of 30 cm, the temperature is about 250 K and varies only 2 to 4 K from noon to dawn. This steady temperature might be useful to designers of telescope facilities on the Moon, but not as a heat sink, because the lunar soil has a very sluggish thermal diffusivity, which will be discussed later.

Magnetic Field

No magnetic field is now being generated inside the Moon, although there was a source of magnetism several billion years ago. Whether this field was generated by a dynamo in a metallic core, as on Earth, or by local, transient events such as meteorite impacts is not known. Whatever its source, the lunar magnetic field is much weaker than is Earth's (ref. 13). On the surface, the lunar magnetic field strength ranges from 3 to 330 gammas (i.e., 1 gamma = 10^{-5} Oe = 10^{-5} gauss). For comparison, the strength of Earth's magnetic field at the Equator is 30 000 gammas. Also, the lunar magnetic field varies locally on the Moon. For example, at the Apollo 16 landing site, the magnetic field strength varied from 113 ± 4 to 327 ± 7 gammas.

There is also a magnetic field external to the Moon, derived from the solar wind. This field ranges in strength from 5 gammas in the free-streaming solar wind to about 10 gammas in Earth's geomagnetic tail, in which the Moon resides 4 days during each lunation.

Micrometeorite Flux

The lack of a significant atmosphere on the Moon allows even the tiniest particles to impact with their full cosmic velocities, ranging from 10 km/sec to several times that value. This rain of minute impactors could damage some structures and instruments on the lunar surface. Almost all lunar rock samples contain numerous microcraters, commonly called zap pits, on surfaces that were exposed to space while on the lunar surface. Studies of lunar rocks (ref. 14) have revealed the average flux of projectiles over the past several hundred million years. The number of craters of a given size (or larger) expected per square meter per year is shown in table III. It is obvious from these data that microcraters in the 1- to 10-μm size range will be common on surfaces exposed at the lunar surface. Even 100-μm craters will not be uncommon, with one produced every other year or so. It appears that sensitive surfaces, such as mirrors on optical telescopes, will have to be protected. The values in table III, however, do not reflect realistic damage potential; the micrometeorites come from the entire sky (2π sr), but many instruments will observe only a small fraction of the sky at any one time. On the other hand, evidence from the Surveyor 3 television camera shroud and from Apollo spacecraft windows (ref. 15) suggests that the current flux of particles capable of producing craters as large as 10 μm across is 10 times greater than indicated from studies of rocks.

Regolith

The lunar regolith, also called lunar soil, is a global veneer of debris generated from underlying bedrock by meteorite impacts. It contains rock and mineral fragments and glasses formed by melting of soil, rock, and minerals. It also contains highly porous particles called agglutinates, which are glass-bonded aggregates of rock and mineral fragments. Agglutinates are produced by micrometeorite impacts into the lunar regolith.

Regolith depth ranges from 2 to 30 m, with most areas in the range of 5 to 10 m. Impacts by micrometeorites have reduced much of the regolith material to a powder. Its grain size ranges from

40 to 268 μm and varies in a highly complex fashion with depth (ref. 16). The chemical composition of the regolith reflects the composition of the underlying bedrock, modified by admixture of material excavated from beneath the uppermost rock or thrown in by distant impacts.

The mechanical properties of lunar regolith samples were measured by Mitchell et al. (ref. 17). The bulk density of the regolith is very low, 0.8 to 1.0 g/cm^3, in the upper few millimeters but increases to 1.5 to 1.8 g/cm^3 at depths of 10 to 20 cm. Its porosity is 35% to 45% in the upper 15 cm and accounts in part for the low density. Except for the uppermost few millimeters, the lunar regolith is more cohesive, 0.1 to 1.0 kN/m^2, than are most terrestrial soils and has an angle of internal friction of 30° to 50°. Agglutinates and shock-damaged rock fragments are weak and break under loads and thus lead to an increase in soil density (ref. 18).

The lunar regolith is an excellent insulator. Its thermal diffusivity at depths >30 cm is 0.7 to 1.0×10^{-4} cm^2/sec, and its thermal conductivity is 0.9 to 1.3×10^{-4} W/cm-K (ref. 19). These values are not surprising considering the high porosity and the lack of air. At depths <30 cm, the thermal diffusivity is somewhat lower.

A small amount of lunar dust might be transported by charge differences built up by photoconductivity effects. Criswell (ref. 20) described a bright glow photographed by Surveyor 7 and explained the phenomenon as levitation of dust grains about 6 μm in radius. The grains were lifted only 3 to 30 cm above the local horizon and had a column density of 5 grains/cm^2. This transport mechanism does not appear to be significant on the lunar surface.

Upper Few Hundred Meters

The upper few hundred meters on the Moon have been intensely fragmented by meteorite impacts. In the heavily cratered highlands and regions underlying mare basalt flows, the fragmental region extends for at least a few kilometers. Consequently, it might be difficult to find extensive areas of intact bedrock.

Data from active seismic experiments (ref. 21) indicate that the velocity of compressional waves is about 100 m/sec at depths of less than 10 m, which is in the regolith, and about 300 m/sec at depths between 10 and 300 m. These low velocities cannot correspond to coherent rock and thus imply that the upper few hundred meters of the lunar surface is rubble (ref. 21). Rocks returned from the highlands confirm the fragmental nature of the upper lunar crust. Most are complicated mixtures of other rocks, and many are weakly consolidated. Furthermore, the rims of all craters typically are composed of weakly consolidated or unconsolidated materials and, therefore, not capable of withstanding tensional stresses.

A few localities might have intact bedrock, however. Many mare basalt flows, for example, form visible layers in crater walls or, as at the Apollo 15 landing site, in the walls of sinuous rills. Also, extensive sheets of impact-generated melt rocks occur on the floors of many large craters, such as Copernicus, which is 95 km in diameter.

Crater Morphologies

Fresh lunar craters as large as 15 km in diameter have a consistent diameter/depth ratio of 5 (ref. 22). More specifically, craters <15 km across follow the relation $R_i = 0.196 D_r^{\ 1.010}$ and craters >15 km diameter follow the relation $R_i = 1.044 D_r^{\ 0.301}$, where R_i is the crater depth and D_r is the diameter as measured from rim crest to rim crest (ref. 22). Large craters are much shallower in proportion to their diameters than are smaller ones. Also, the crater morphology changes as a crater is eroded by meteorite bombardment, during which a crater becomes wider and shallower, and thereby the diameter/depth ratio is increased. Finally, as noted previously, rim materials consist of weak, unconsolidated rock. This composition could cause problems in the construction of some facilities, though not of Arecibo-type antennas as these are constructed with almost no tensional forces, as Frank Drake noted during the Workshop on Astronomical Observations from a Lunar Base.

Acknowledgments

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References

1. Burke, B. F.: Astronomical Interferometry on the Moon. In Lunar Bases and Space Activities in the 21st Century, W. W. Mendell, ed., Lunar and Planetary Institute (Houston, Tex.), 1985, pp. 281-291.

2. Burns, J.: A Moon-Earth Radio Interferometer. In Lunar Bases and Space Activities in the 21st Century, W. W. Mendell, ed., Lunar and Planetary Institute (Houston, Tex.), 1985, pp. 293-300.

3. Goins, N. R.; Dainty, A. M.; and Toksoz, M. N.: Seismic Energy Release of the Moon. J. Geophys. Res., vol. 86, 1981, pp. 378-388.

4. Nakamura, Y.; Latham, G. V.; Dorman, H. J.; Ibrahim, A.-B. K.; Koyama, J.; and Horvath, P.: Shallow Moonquakes: Depth, Distribution and Implications as to the Present State of the Lunar Interior. Proc. 10th Lunar Planet. Sci. Conf., 1979, pp. 2299-2309.

5. Lammlein, D. R.; Latham, G. V.; Dorman, J.; Nakamura, Y.; and Ewing, M.: Lunar Seismicity, Structure, and Tectonics. Rev. Geophys. Space Phys., vol. 12, 1974, pp. 1-21.

6. Hoffman, J. H.; Hodges, R. R., Jr.; and Johnson, F. S.: Lunar Atmospheric Composition Results From Apollo 17. Proc. 4th Lunar Sci. Conf., 1973, pp. 2865-2875.

7. Johnson, S. W.: Engineering for a 21st Century Lunar Observatory. Submitted to J. Aerospace Eng., 1986.

8. Hodges, R. R., Jr.: The Escape of Solar-Wind Carbon From the Moon. Proc. 7th Lunar Sci. Conf., 1976, pp. 493-500.

9. Vondrak, R. R.: Creation of an Artificial Lunar Atmosphere. Nature, vol. 248, 1974, pp. 657-659.

10. Johnson, F. S.: Lunar Atmosphere. Rev. Geophys. Space Phys., vol. 9, 1971, pp. 813-823.

11. Keihm, S. J.; and Langseth, M. G.: Surface Brightness Temperatures at the Apollo 17 Heat Flow Site: Thermal Conductivity of the Upper 15 cm of Regolith. Proc. 4th Lunar Sci. Conf., 1973, pp. 2503-2513.

12. Mendell, W. W.; and Low, F. J.: Low-Resolution Differential Drift Scan of the Moon at 22 Microns. J. Geophys. Res., 1970, pp. 3319-3324.

13. Dyal, P.; Parkin, C. W.; and Daly, W. D.: Magnetism and the Interior of the Moon. Rev. Geophys. Space Phys., vol. 12, 1974, pp. 568-591.

14. Fechtig, H.; Hartung, J. B.; Nagel, K.; and Neukum, G.: Lunar Microcrater Studies, Derived Meteoroid Fluxes, and Comparison with Satellite-Borne Experiments. Proc. 5th Lunar Sci. Conf., 1974, pp. 2463-2474.

15. Cour-Palais, B. G.: The Current Micrometeoroid Flux at the Moon for Masses $<10^{-7}$ g From the Apollo Window and Surveyor 3 TV Camera Results. Proc. 5th Lunar Sci. Conf., 1974, pp. 2451-2462.

16. Heiken, G.: Petrology of Lunar Soils. Rev. Geophys. Space Phys. vol. 13, 1975, pp. 567-587.

17. Mitchell, J. K.; Houston, W. N.; Scott, R. F.; Costes, N. C.; Carrier, W. D. III; and Bromwell, L. G.: Mechnical Properties of Lunar Soil: Density, Porosity, Cohesion, and Angle of Internal Friction. Proc. 3rd Lunar Sci. Conf., 1972, pp. 3235-3253.

18. Carrier, W. D. III; Bromwell, L. G.; and Martin, R. T.: Behavior of Returned Lunar Soil in Vacuum. J. Soil Mech. Found. Div., ASCE, vol. 99, 1973, pp. 979-996.

19. Langseth, M. G.; Keihm, S. J.; and Peters, K.: Revised Lunar Heat-Flow Values. Proc. 7th Lunar Sci. Conf., 1976, pp. 3143-3171.

20. Criswell, D.: Lunar Dust Motion. Proc. 3rd Lunar Sci. Conf., 1972, pp. 2671-2680.

21. Cooper, M. R.; Kovach, R. L.; and Watkins, J. S.: Lunar Near-Surface Structure. Rev. Geophys. Space Phys., vol. 12, 1974, pp. 291-308.

22. Pike, R. J.: Depth/Diameter Relations of Fresh Lunar Craters: Revision From Spacecraft Data. Geophys. Res. Lett., vol. 1, 1974, pp. 291-294.

TABLE I.- COMPARISON OF MOONQUAKE AND EARTHQUAKE INTENSITIES

[From ref. 3]

Parameter	Moon	Earth
Frequency of events, no/yr	5 shallow ($m > 2.2$)[a] 500 deep ($m > 1.6$)	10^4 ($m > 4$)
Energy release of largest event, ergs	2×10^{17} (shallow) 1×10^{13} (deep)	10^{26}
Magnitude of largest event	4.8 (shallow) 3.0 (deep)	9.5
Seismic energy release, ergs/yr	2×10^{17} (shallow) 8×10^{13} (deep)	10^{25}

[a] m = magnitude.

TABLE II.- COMPOSITION OF THE LUNAR ATMOSPHERE AT NIGHT

[From ref. 6]

Gas	Concentration, molecules/cm^3
H_2	6.5×10^4
^4He	4×10^4
^{20}Ne	8×10^4
^{36}Ar	3×10^3
^{40}Ar	7×10^3
O_2	$<2 \times 10^2$
CO_2[a]	$<3 \times 10^3$

[a] Carbon gases (CO_2, CO, CH_4) probably dominate the daytime lunar atmosphere (ref. 8).

TABLE III.- MICROMETEORITE FLUXES ON THE MOON

[Calculated from data in ref. 14]

Crater diameter, μm	Flux, craters/m^2-yr
≥0.1	30 000
≥1.0	1 200
≥10	300
≥100	.6
≥1000	.001

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CRYOGENIC, POLAR LUNAR OBSERVATORIES

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Discussion

Though it has been known for centuries that the Moon's polar axis is nearly normal to the plane of the ecliptic (ref. 1 and fig. 1), not much attention seems to have been paid to the resulting astronomical possibilities. In permanently shadowed crater bottoms near the lunar poles (figs. 2 and 3), very low temperatures must prevail. Just how low is unknown because no direct measurements have yet been made. However, measurements in other lunar regions and various theoretical investigations (refs. 2 to 6) suggest that ambient ground temperatures, resulting from the balance among radiation to space, sunlight scattered into the shadowed areas, starlight and other cosmic energy sources, and the Moon's internal heat flow, may be as low as 40 K.

A telescope located in one of these low, dark, polar regions could operate with only passive cooling at that temperature or perhaps lower, depending on how well it could be insulated from the ground and surrounded by radiation shields to block heat and light from any nearby warm or illuminated objects. Of course, such a site affords access to only half of the sky at most, but within the sky not masked by the horizon, the telescope could continuously track any object for as long as desired. Ideally, there would be two telescopes, one at each pole. With this arrangement, all but a small part of the sky (near the ecliptic) could be covered without the engineering problems of the 2-week hot days and the 2-week cold nights encountered anywhere else on the Moon.

At lower latitudes on the Moon, both the U.S. Surveyor spacecraft and the U.S.S.R. Lunokhod rovers observed a postsunset glow (fig. 4) believed to be sunlight scattered from small dust particles moving under electrostatic forces within a few meters of the surface. Since the Sun is always near the horizon at the poles, this phenomenon may be different there. It could, from the point of view of light scattering into a telescope, be either better or worse than at the equator. The only way to tell is to make measurements. These, with other environmental and topographic data, would be part of the site surveys that are essential for planning a lunar polar observatory.

The possibility of passive cooling to temperatures of tens of kelvins or lower makes it logical to consider this unique lunar polar environment as a locale primarily for infrared and submillimeter astronomy and secondarily for any other instrumentation benefiting from low thermal noise. Other advantages of lunar polar base sites are discussed in reference 7.

Why should astronomers concern themselves now with this prospect? There are two reasons. First, automated lunar exploring missions are, after a gap of many years, now being seriously proposed by the U.S.S.R., the United States, and Japan. These missions can and should make the first polar measurements needed in an astronomical site survey. Astronomers should seek to influence the mission planning which would otherwise be done entirely in the geosciences community. Second, the suitably dark and cold territories on the Moon are surely small, probably only hundreds of kilometers in extent, and thus need to be protected by international agreement just as does the radio-quiet region on the Moon's far side. Astronomers have a long and successful background in establishing such agreements. With these preparatory steps in progress, scientists requiring cryogenic instruments will be in a good position to benefit when, for whatever reasons, the United States, the U.S.S.R., or both decide to resume the exploration and settlement of the Moon.

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References

1. Colombo, G.: Cassini's Second and Third Laws. In Measure of the Moon, Z. Kopal and C. Goudas, eds., D. Reidel (Dordrecht) and Gordon and Breach (New York), 1966, pp. 12-22.

2. Watson, K.; Murray, B. C.; and Brown, H.: The Behavior of Volatiles on the Lunar Surface. J. Geophys. Res., vol. 66, no. 9, 1961, p. 3033.

3. Gary, B. L.; Stacey, J. M.; and Drake, F. D.: Radiometric Mapping of the Moon at 3 Millimeters Wavelength. Astrophys. J. Suppl. Ser., vol. 12, 1965, p. 239.

4. Arnold, J. R.: Ice in the Lunar Polar Regions. J. Geophys. Res., vol. 84, 1979, pp. 5659-5668.

5. Lanzerotti, L. J.; Brown, W. L.; and Johnson, R. E.: Ice in the Polar Regions of the Moon. J. Geophys. Res., vol. 86, 1981, pp. 3949-3950.

6. Keihm, S. J.: Interpretation of the Lunar Microwave Brightness Temperature Spectrum: Feasibility of Orbital Heat Flow Mapping. Icarus, vol. 60, 1984, pp. 568-589.

7. Burke, J. D.: Merits of a Lunar Polar Base Location. In Lunar Bases and Space Activities of the 21st Century, W. W. Mendell, ed., Lunar and Planetary Institute (Houston, Tex.), 1986.

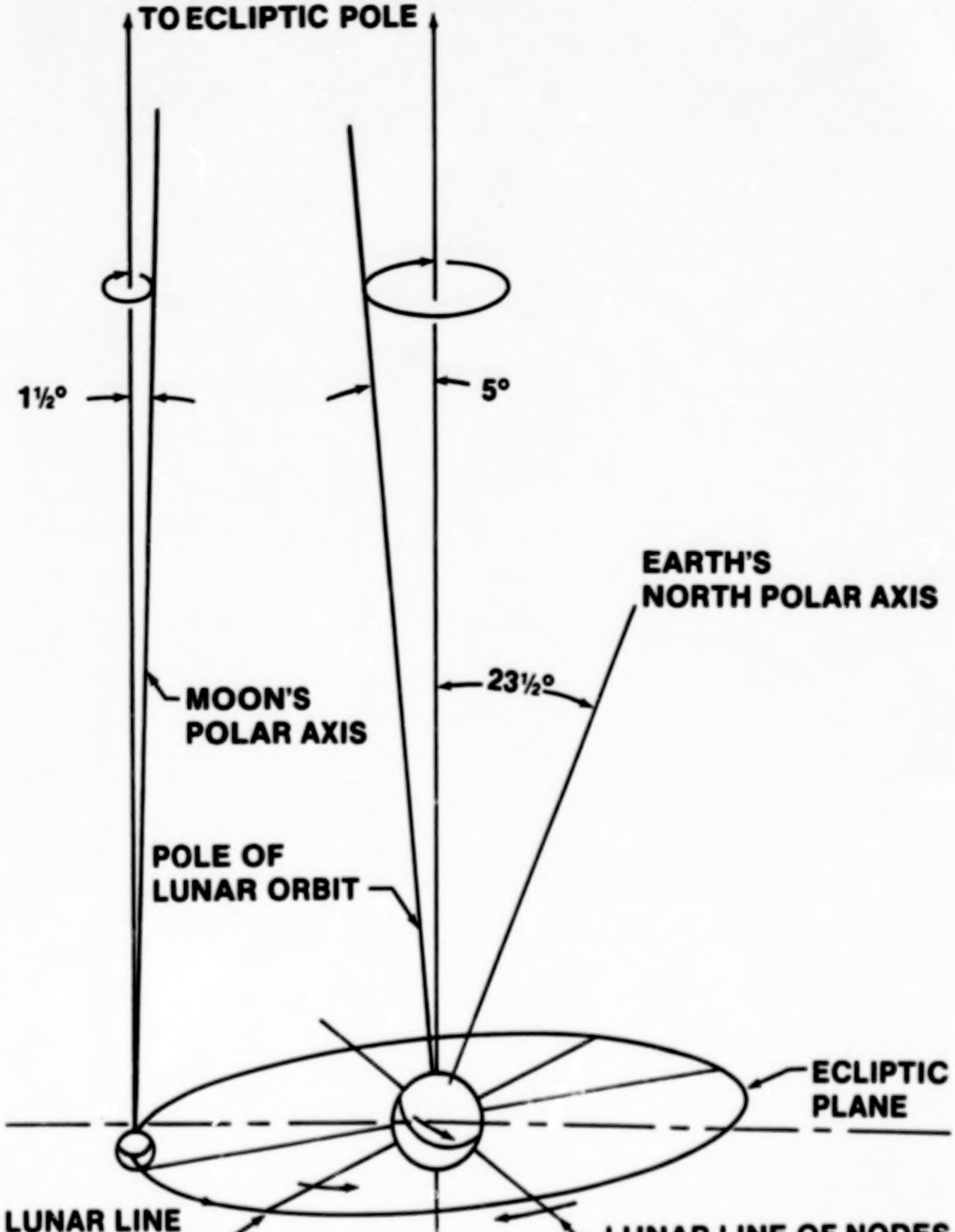
TO ECLIPTIC POLE
1½°
5°
EARTH'S NORTH POLAR AXIS
23½°
MOON'S POLAR AXIS
POLE OF LUNAR ORBIT
ECLIPTIC PLANE
LUNAR LINE OF APSIDES
LUNAR LINE OF NODES

Figure 1.- An illustration of the motions of Earth and Moon. Despite the inclination and precession of Earth's polar axis and of the Moon's orbit (as described by G. D. Cassini in 1693), sunlight is always nearly horizontal at the lunar poles.

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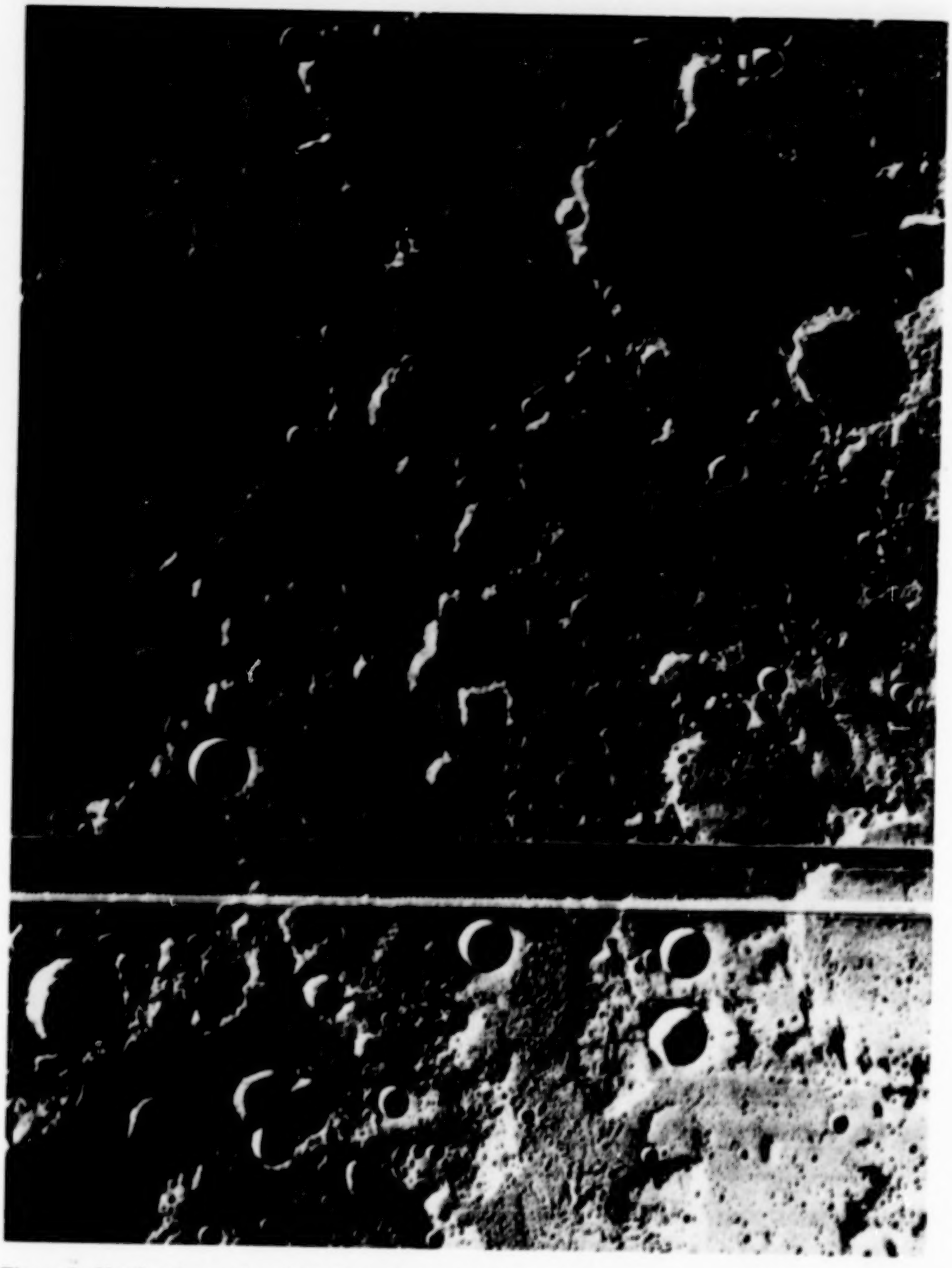

Figure 2.- North polar region of the Moon. Craters Peary and Byrd, at top center and upper right, are about 80 km across. Pole is at upper left. Portion of Lunar Orbiter 4 frame 176H1.

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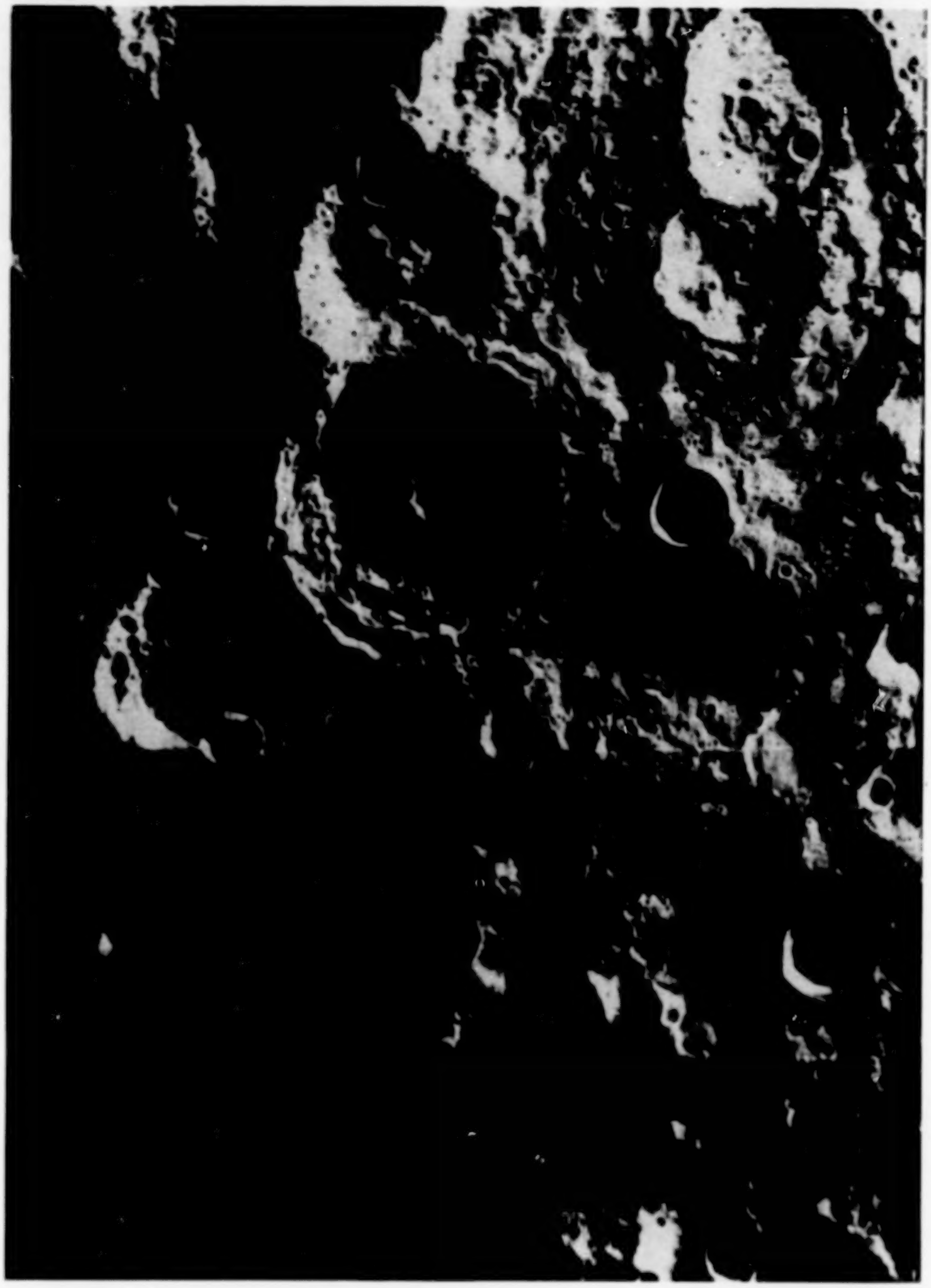

Figure 3.- South polar region of the Moon. Crater Amundsen, near center, is about 100 km across. Pole is about halfway from Amundsen to bottom of frame. Portion of Lunar Orbiter 4 frame 005H3.

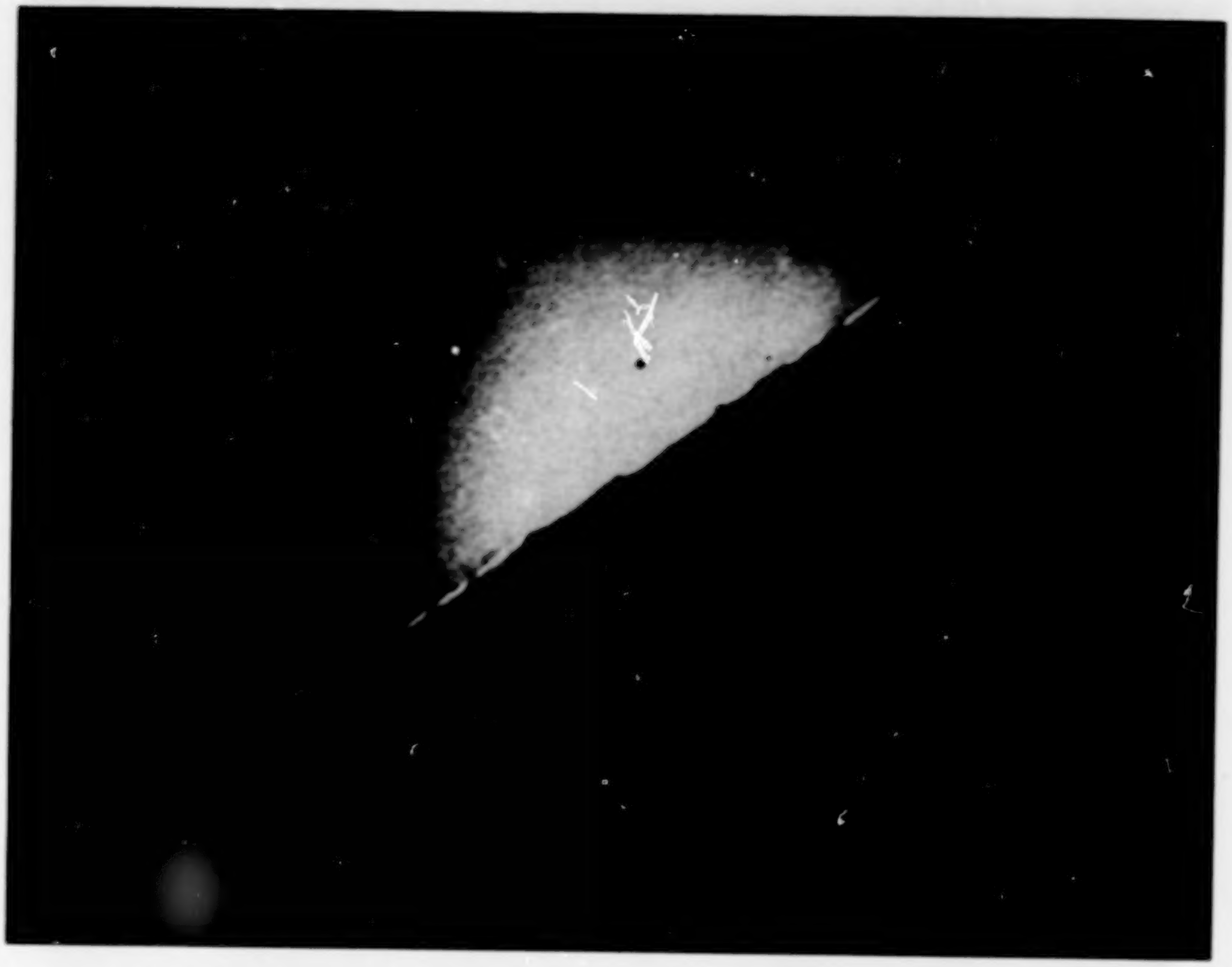

Figure 4.- Postsunset glow along lunar horizon, observed by Surveyor spacecraft.

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OVERVIEW OF LUNAR-BASED ASTRONOMY

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Time Scales

Barring the collapse of high-technology civilization, extensive settlement and utilization of the Moon will certainly occur. The only question is the timing. An Apollo-scale effort could result in setting up an initial lunar base within a decade. More realistically, lunar base development should and presumably will follow that of Space Station, and both of these developments will surely have funding constraints preventing them from progressing at the fastest possible rate. Thus, 15 to 20 years is a plausible target, at least for the Western World, for establishing our first and initially very small permanently manned lunar facility. However, such activities tend to exponentiate, and it is reasonable to expect that by 40 or 50 years hence, there will exist substantial scientific and industrial facilities on the Moon. These next four and a half decades happen to cover the effective working lifespan of astronomers currently getting their Ph.D.'s. They also carry us to the extreme range of reliability of my crystal ball. Accordingly, most of what follows will deal with this coming long generation — the only one we can directly influence and define with any plausible assurance. (As with any crystal ball gazing, the ideas expressed represent a personal viewpoint with which the reader may well disagree.)

In this frame of reference, I visualize lunar astronomy as having four major phases, compressed but analogous to those experienced in the development of the Americas.

First is the pioneering stage, during which nearly all the effort is spent on simply getting there and building survival facilities, with extremely limited resources available for other activities. This stage is likely to occupy most of the decade until around 2010 and can feature only simple scientific equipment which is easily carried, installed, and operated.

Next comes a period of initial settlement, when access has become fairly easy and enough infrastructure exists to allow the beginning of concentration on using the environment. On the Moon, this period could well occur in the decade around 2010-2020 and might be characterized by the installation of several relatively substantial astronomical facilities, but essentially everything needed would still have to be brought from Earth at great cost.

Third is the time of consolidation, featuring routine low-cost access, significant population, and some local facilities for manufacturing. Given a reasonable pace of lunar development, this phase could begin to become real in the period around 2020-2040. It would open up new kinds of opportunities for astronomy, including not only larger units manufactured on Earth but also some usage of local resources.

Eventually will come the phase of maturity, when there will be substantial self-sufficiency and when lunar civilization will begin its own evolution in parallel with that of Earth. Here, speculation can be cheerfully unfettered, because few of those who now believe themselves qualified to speculate will be around to blush. Nevertheless, I do not intend to speculate.

These phases offer a framework in which to place plausible sequences and rough estimates of time scale for lunar astronomical facilities.

The Lunar Environment for Astronomy

The Moon offers both significant advantages and drawbacks for astronomy. Recognition of these characteristics can clarify the objectives toward which developments should be directed and can help to inhibit premature or excessive selling of lunar developments on the basis of astronomy.

Lunar Advantages and Opportunities

Some advantages and opportunities of the lunar environment for astronomy are discussed in the following paragraphs.

Vacuum.- For all practical purposes (other than perhaps low-frequency radio astronomy), the Moon has an excellent vacuum. Its tenuous atmosphere acts as a collisionless gas, with the molecules traveling in ballistic trajectories. The total nighttime surface concentration of known species (hydrogen, helium, neon, and argon) is only about 2×10^5 molecules cm^{-3}, with daytime concentrations substantially lower because of heating and escape of gases. These values are characteristic of the Earth's atmosphere at upper ionospheric heights and constitute an ultrahigh vacuum in laboratory terms. The lunar surface thus offers a splendid environment for diffraction-limited imagery, for phase-coherent interferometry, and perhaps for detectors using naked cathodes. It also offers the prospect of indefinitely long lifetimes for reflective or transmissive coatings on optical elements.

Dark, cold sky.- The tenuous atmosphere, the lack of appreciable magnetic field, and the apparently very low ion density in the lunar ionosphere all should conduce to an effective absence of airglow. Accordingly, the lunar night sky should be about four times darker than is typically experienced at Earth-based observatories, and spectra will be free of the degrading contamination of sky emission lines. If telescopes are appropriately shielded from direct and reflected sunlight, even the daytime sky should appear amply dark for many kinds of observation. The sky will be even darker than seen from near-Earth orbit, because of the absence of spacecraft-type glow and of the very high terrestrial airglow. For wavelengths at which thermal background is important, the nighttime temperature of an entire system which is well insulated and shielded from the ground can easily be held to a deep cryogenic state even without special cooling. This advantage could lead to superb infrared (IR) performance.

Stable inertial platform.- It is expensive and difficult to aim and guide instruments from free-flyers which lack anything solid to push against. The Moon offers the advantages of space observing along with the simplicity and economy of terrestrial telescope mountings. In addition, separate structures firmly rooted in the lunar surface should be almost absolutely stable in their relative positions and orientations for indefinitely long times. Lunar seismic activity is orders of magnitude less than that of the Earth. Any differential effects between interferometer structures caused by expansion and contraction of the lunar surface between day and night will not only be exceedingly small but can be completely eliminated by putting foundations at a depth of several meters, where the regolith is essentially immune to the diurnal thermal wave. Solid-body tides caused by the Sun have amplitudes of centimeters, but their lunar-diameter wavelength guarantees that any differential tilt effects between line-of-sight interferometer elements will be only second order, and any changes of path length will be of even lower order yet.

Proximity of people and support facilities.- Although nearly all lunar astronomy will involve remote and automated equipment, the immediate proximity of people, service gear, cryogenics, etc., for operation, maintenance, and modification will prove advantageous for many kinds of programs.

Rotation.- The lunar rotation allows properly located observatories to view essentially all the sky. The slow rotation produces nights lasting for 2 weeks and thus permits extremely deep exposures on very faint sources or the very long uninterrupted time series on variable objects which are so necessary to permit solution for complex periodicities.

Avoidance of Earth.- The Earth and/or its human activities enhance the noise background at nearly all wavelengths of observation. The Moon is sufficiently far away that even the Earth-facing side is fairly well quarantined, and the back side is the only place in the universe which is never exposed to Earth. This latter factor is likely to become of absolutely crucial importance when later generations of radio astronomers face the challenge of building ultimately-low-noise systems for purposes of science and probably of the search for extraterrestrial intelligence (SETI).

Low gravity.- When the day finally comes for erection of very large structures on the lunar surface, the 1/6g will appreciably simplify engineering problems compared with their Earth-based counterparts. Also, the lunar gravity will continuously clean out contamination, which is unfortunately not the case for orbiting stations.

Readymade landforms.- The smooth and symmetrical bowls of some lunar craters, coupled with the low gravity, suggest that, someday, construction of Arecibo-type antennas as large as perhaps 10 km in diameter should be feasible.

Raw material.- The Moon offers an inexhaustible supply of raw material. Unprocessed, it serves for shielding people and some kinds of equipment against cosmic rays. When processing facilities are in place, locally produced metals, ceramics, fibers, etc., will greatly reduce the dependence on Earth for supply. This factor will become important should very-large-scale engineering of astronomical facilities be undertaken.

Drawbacks of the Lunar Environment

Some drawbacks of the lunar environment for astronomy are discussed in the following paragraphs.

Cost.- At present, it costs several hundred times as much to put a given astronomical facility in Earth orbit as to build it on the ground, and — certainly in the early years — it will cost at least a further factor of 10 to put it on the Moon. Shipping costs in the range of $\$10^5$/kg suggest that during the pioneering and early settlement stages, any lunar astronomical instruments should be relatively simple and lightweight, be of high scientific importance, and require the lunar location for feasibility or cost-effectiveness.

Gravity.- Although low, the lunar gravity is still present and will be an increasingly important cost driver as the sizes of lunar instruments grow.

Vacuum.- Though indispensable for many kinds of astronomy, the lunar vacuum environment will render many kinds of human construction and operation activities exceedingly cumbersome, dangerous, and expensive. During at least the pioneering and settlement phases, this factor will require a very high degree of terrestrial prefabrication of astronomical equipment destined for the Moon. For larger scale construction, robots will certainly be required.

Dust.- The Apollo astronauts found electrostatically clinging lunar dust to be a nuisance. If carelessly splashed around delicate or sensitive equipment, dust might prove to be a significant problem. However, the fear that naturally saltating dust would soon coat anything on the lunar surface seems not to be realized, because the three U.S. lunar laser reflectors which have lain open on the lunar surface for the past 15 years have yet to show any measurable loss of reflectivity.

Ionosphere.- The actual electron density in the lunar ionosphere (poorly known) could be a limiting factor for very low frequency radio astronomy from the Moon and might possibly prove to be a noise source for some kinds of detectors.

The Competition

Surface

As noted previously, for the next several decades, it is likely that attempting an astronomical observing program from the Moon will cost at least a thousand times more than it would to set up the program on Earth. In other words, if it is possible at all — even with great difficulty — to do the work from the Earth's surface, this will normally remain the preferred approach.

Space

Advantages of locating an astronomical facility in space rather than on the lunar surface are discussed.

Cost.- Once again, at least until we reach the consolidation phase of lunar utilization, the expense of performing space-based astronomy from Earth orbit rather than from the Moon will be about an order of magnitude less. Until this ratio changes, experiments and observations which can be done from Earth orbit will continue to be concentrated there. What might change this? The development of very-low-cost orbital transfer vehicles (e.g., solar sails, nuclear or solar-electric propulsion, oxygen supply from the Moon) will help. Invention of a practicable lunar landing system not requiring retrorockets would be a great step forward. Exotic lunar takeoff systems not requiring rockets (e.g., electromagnetic launchers) will be important. Such systems will presumably be available someday, but for the next 20 to 30 years, only improved orbital transfer vehicles appear promising. During this period, any substantial lunar astronomy facilities should be only those which uniquely require the Moon and which can afford to be there.

Advantages of orbital space over the lunar surface.- Compared with lunar basing, location in Earth orbit offers at least one immediate and two major general advantages for astronomical instrumentation.

First is a question of timing. We already can work effectively in Earth orbit, whereas it will be at least 15 to 20 years before any significant instrumentation can be built on the Moon. This fact gives a great head start for evolving technology and for accomplishing science and undoubtedly will have some inhibiting effect on planning and resources which might otherwise go into developing lunar facilities.

More fundamentally, the lack of gravity loading means that orbiting structures of virtually any size can be built from exceedingly lightweight, low-cost materials, and, with prefabrication, the assembly of these structures in space will be easier than with the more elaborate construction equipment and techniques required in a gravity field. Normally, the larger the structure, the greater the gain will be from constructing it in free space. Secondly, for interferometer systems not requiring continuous structure, arbitrarily large baselines are possible in principle, and ingenious techniques are being developed for baseline monitoring and stationkeeping. In general, lunar astronomy will likely be limited to structures of only modest size and baseline compared to those which will be built in free space. (Arecibo-type antennas may be an exception to this principle.)

Lunar Astronomy

In light of all the factors discussed previously, what kinds of developments should we be planning and dreaming about for lunar-based astronomy, at least during the first three phases of lunar exploitation? The remainder of this symposium deals with this question in detail, so I only note here some of the possible high spots. I also specifically omit high-energy physics and astronomy, leaving these fields to the experts and to whatever case they can make for putting such facilities on the Moon rather than in orbit.

Pioneering Phase

I am aware of only four proposed astronomical facilities which appear to satisfy all the criteria of being scientifically important and needing the Moon, while also being both affordable and probably more cost-effective than any other approach, during the pioneering initial Moon-base phase. These are

1. A very large, very low frequency radio interferometer, with tiny antenna elements simply laid out on the lunar surface

2. One (later a set of) extremely lightweight, small (~40-cm class) telescope(s) equipped with high-quality photometers and spectrographs to study submillimagnitude and meter-per-second stellar seismology for long uninterrupted runs on each star

3. A modest (3-m class) cryogenic IR/submillimeter antenna system in a shielded place on the Moon which may well prove cost-effective compared with the expense of building and free-flying such a system in Earth orbit and keeping it cold over very long periods of time

4. In the later stages of this phase, an ultraviolet (UV)/optical interferometer of substantial (kilometers) baseline (This may well be the only project of such high scientific importance, which is also uniquely feasible on the Moon, as to be something of a science driver for the lunar base.)

Settlement Phase

The settlement phase should open up possibilities for developing sites remote from the initial lunar base (which will probably be Earth-facing). If these new sites included startup polar and far-side stations, they would permit the beginning of initially small and specialized observatories capable of taking advantage, respectively, of fully continuous monitoring of certain objects and of the radio quiet of the lunar far side.

A UV/optical interferometer with more and larger elements will become feasible; also, one or more lightweight general-purpose telescopes of the several-meter class may prove cost-effective. By this time, free-flying observatories of modest size will still cost at least several hundred million dollars, and it may become possible to build, ship, erect, and operate comparable telescopes on the Moon for significantly less cost than for their free-flying counterparts.

Consolidation Phase

In the consolidation phase, the overall state of lunar development and robotics should have reached the point at which quite substantial systems can be contemplated. These systems may include more conventional radio interferometers with baselines of hundreds of kilometers and optical interferometers with baselines of tens of kilometers; even the construction of Arecibo-type antennas may be possible. And it is likely that radio observatories of ultimate low-noise performance, for science and for SETI, will be in operation.

Conclusions

By the mid-21st century, it is reasonable to expect that astronomy should have developed several major domains, each with its areas of technical preeminence or cost-effectiveness.

1. Ground-based work will continue, because of its accessibility, its convenience, its economy, its established funding, its continued effectivity, and because of the fact that for some important purposes such as spectroscopy, many kinds of photons can be collected almost as well on the ground as anywhere.

2. Earth-orbital work will remain useful, primarily for convenience of access in constructing and operating very large space systems, but can be expected to have migrated largely to orbits near geosynchronous in order to avoid debris in low orbits and the inconvenience of 90-minute days.

3. Deep-space studies will feature not only probes but extensive systems for extremely-long-baseline (many astronomical unit) studies at wavelengths from gamma rays through visible and IR out to radio.

4. Finally, lunar astronomy will have found important permanent applications along lines such as are discussed in this symposium and, no doubt, others quite unsuspected by us today.

PART II
HIGH-ENERGY, OPTICAL, AND INFRARED TELESCOPES

In part II of these proceedings, ideas for individual lunar-based telescopes at the shortest x-ray and gamma-ray wavelengths, at optical and infrared (IR) wavelengths, and also for high-energy cosmic rays are described. P. Gorenstein leads off with a discussion of the advantages of the Moon for x-ray astronomy. He concludes that large-area detectors connected to long-focal-length telescopes will provide superior signal-to-noise ratios and resolution compared to any high-energy-photon observatories that can be practically placed in Earth orbit. J. Linsley reviews the state of cosmic-ray physics in the second paper of part II and concludes that the nonexistent lunar magnetic field, the low lunar radiation background, and the lack of an atmosphere on the Moon provide an excellent environment for the study of high-energy primary cosmic rays. H. S. Stockman, in the third paper, considers the growth of space observatories, especially at optical wavelengths, during the next several decades. He concludes that large-aperture optical telescopes on the Moon, possibly constructed of lunar glasses, will be very competitive with and in some instances superior to Earth-orbiting telescopes. An innovative idea for an optical interferometer is proposed by B. Burke in the fourth paper. Many of the workshop participants viewed this proposal as the single most important advance in astronomy for the 21st century, in that it would best utilize the remarkable stability of the lunar surface. In the final paper in part II, D. Lester describes the manner in which infrared astronomy could benefit from a lunar base. He concludes that the low lunar vacuum and massive thermal shielding provide an opportunity for simple, but very sensitive, large-area IR detectors that are passively cooled.

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HIGH-ENERGY ASTRONOMY FROM A LUNAR BASE

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Introduction

Astronomical investigations in the x-ray (0.2 to 100 keV) and gamma-ray (10^{-1} to 10^4 GeV) regions of the electromagnetic spectrum were made possible by spacecraft above the absorption of the Earth's atmosphere. For the future, x-ray and gamma-ray telescopes that are considerably larger and more massive than those currently under development for the next generation of satellite experiments are envisioned. Indeed, the collecting area of these instruments is limited by the size and weight capacity of current spacecraft rather than by any intrinsic difficulty in constructing larger detectors or telescopes. The virtually unlimited "real estate" of the lunar surface would accommodate instruments with considerably more capability than is possible on an Earth-orbiting platform. Consequently, a lunar base offers investigators the best opportunity to achieve the ultimate potential in high-energy astronomy.

First-generation high-energy astronomy observatories on the Moon will consist of telescope and detector components that are manufactured on Earth and aligned in situ. As a lunar manufacturing capability evolves, it may become possible to fabricate the heavy telescope components by using the Moon's low gravity and good vacuum.

The unlimited space of a lunar base as compared to an Earth-orbiting station offers the following advantages.

1. Large space: Many large-collecting-area x-ray and gamma-ray instruments can be accommodated at the same time.

2. Stable baseline: Long focal length between telescopes and detectors can result in configurations with very high resolving power.

3. Long duration: Inactive instruments need not be removed to make room for other telescopes needed.

4. Assembly of large instruments: Manned activity on the lunar surface is less difficult than extravehicular activities from a space station. Using common surveying techniques, lunar astronauts can align various components of a telescope system, change the configuration for other measurements, or incorporate improved technology.

5. Service: Sufficient space is available for a large supply of consumables, replacement parts, and dedicated computers.

6. Expandability: Telescope systems, particularly those of a modular type, can be developed incrementally in reserved spaces.

7. Observing: Continuous 14-day coverage of cosmic sources is possible.

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The drawbacks of a lunar base – the cost of transporting cargo to the Moon and the difficulties of adapting to the day-night temperature extremes – would be ameliorated as transport capability improves and as more experience is gained on lunar surface operations. There is an intrinsic problem in that the absence of a magnetic field on the Moon results in a cosmic-ray background that is four times higher compared to near-Earth orbit. Although this increased background is disadvantageous to some x-ray and gamma-ray detector systems, it is not a major impediment for focusing x-ray telescopes or for gamma-ray telescopes which measure the arrival directions of individual photons. These telescopes are capable of discriminating against a diffuse background on the basis of the source's position.

X-Ray and Gamma-Ray Instruments

Three generic classes of instruments are optimum for deployment on a lunar base. They are systems with one or more of the following characteristics.

1. Very high throughput: Collecting area of 10^5 cm^2 or more

2. Very long focal length: Very high angular resolution when used in conjunction with occulting aperture masks

3. Broad sky coverage, 2π sr: Studies of temporal variability in many objects simultaneously, including burst sources, flares, and transients, as well as monitoring the activity cycles of many galactic and extragalactic sources

Photon fluxes (but not necessarily energy fluxes) of sources in the x-ray and gamma-ray bands tend to be relatively low compared to those of optical and radio-emitting objects. Hence, high throughput is a prerequisite for detailed astrophysical studies that go beyond merely detecting and cataloging sources. Investigators have stated that collecting areas exceeding 10^5 cm^2 are needed to satisfy their requirements in the next century. The objectives of such instruments include imaging, spectroscopy, and measurements of temporal variability.

An artist's conception of a high-throughput x-ray telescope system on the lunar surface is shown in figure 1. The instrument shown is the large-area modular array of reflectors (LAMAR), which consists of arrays of independent modules with imaging x-ray telescopes and detectors. Although the LAMAR is shown as a compact unit mounted in a single large pointing system, in practice, the array is more likely to be in a modular pointing system to facilitate service and insertion of gratings and crystals for spectroscopy and polarization measurements. A small version of the LAMAR with about 10^3 cm^2 of collecting area at an energy of 1 keV is being developed as a Space Shuttle experiment (ref. 1). This sketch (fig. 1) could represent other instruments as well, including coded-aperture devices for hard x-rays and low-energy gamma rays and a system of spark chambers for gamma rays with energies greater than 100 MeV. In contrast to the isolation afforded by a lunar base, it seems virtually impossible to accommodate and maintain all of these large systems in the close confinement of an Earth-orbit platform simultaneously for long periods without encountering mutual interference.

The angular resolution of a conventional x-ray telescope is limited by optical tolerances to perhaps 0.1 second of arc. Any further improvement would require a different approach, such as one based on occultation involving a long, stable baseline between apertures and detectors rather than on accuracy in the polishing process. For example, two 2-mm apertures separated by a 20-km baseline define a direction to within 0.02 arcsec. For wavelengths shorter than 0.4 nm, diffraction through 2-mm apertures will be below the level of 0.02 arcsec. It is possible to specify a variety of long-baseline instruments on the order of these dimensions that can achieve higher angular resolution over a limited angular range than is currently achievable by the best focusing telescopes.

One approach is shown in figure 2. The instrument is a variation of the scanning modulation collimator of the High-Energy Astronomy Observatory (HEAO-1 and HEAO-3) experiment (refs. 2 and 3) and is considerably larger. Rising or setting of sources caused by lunar rotation provides the scan. There is a 20-km baseline between two "picket fence" collimators that are presumed to be located near the equator of the Moon. The collimators are repetitively open for a distance of 2 mm and opaque for 6 mm. A 10^4-cm^2 moderate-resolution x-ray telescope, e.g., a subset of the LAMAR experiment (fig. 1), is behind the second collimator and serves as a detector.

The telescope, as compared to a nonimaging detector, eliminates background and confusion from multiple sources. If a point source is in the field of view, the modulated intensity of the image as a function of time is a series of perfect triangles as the Moon rotates. If the source has finite structure on a scale between 0.01 and 0.1 arcsec, it can be derived from a deconvolution of the shape of the modulation. Intrinsic time variations in the source are corrected by monitoring the source with a portion of the detector array that is outside the collimators. If the source can be tracked for 1° of lunar rotation, or 2 hours, as it rises or sets, there would be sufficient counts for studying the structure of the faintest extragalactic sources detected by the Einstein Observatory (HEAO-2). The objective of such studies is the structure of the central regions of quasars and other active galactic nuclei, including the existence of jets projecting from them. Resolving multiple images due to gravitational lensing effects is another objective.

The picket fence collimators have to be precisely periodic. For each degree of tracking, the distant one would either have to be 320 m high (at a 20-km distance) or have to move along a 320-m vertical track at a precisely known rate slightly different than that of the Moon's rotation. Alternatively, the nearer collimator and telescope could be placed on an elevator that is situated in a crater (fig. 3). The elevation of these instruments above the crater floor is adjusted to maintain the line of sight to the distant collimator along a constant direction on the celestial sphere as the source rises or sets. There are potentially hundreds of interesting sources in a 1° by 360° band of azimuth along the lunar equator. The amount of sky accessible to the instrument could be increased by providing a means of rotating the axis of the system off the lunar equator. In particular, the distant collimator is placed on a circumferential track around the near collimator-detector. Each 320-m segment of track length adds another 1° band of sky. A semicircle, or about 66 km of track, would bring nearly the full celestial sphere within reach of the instrument.

Although this particular instrument provides angular resolution in only one dimension, variations of this configuration can be effective for two dimensions. For example, the Japanese satellite *Hinotori* obtained x-ray images of the Sun with a rotating modulation collimator (ref. [illegible]). In analogy to that instrument, the two widely separated collimators of the lunar-based observatory are slowly rotated about the same axial direction in space. Their rotation rates are synchronized to a common clock. The Fourier transform of the intensity modulations provides the high-resolution image. Obviously, many details need to be worked out, including the most practical means of rotating the collimators and determining whether they should be integral or modular. Simulation studies would clarify the resolving power of this configuration.

The first reaction of someone habituated to working within the limited confines of a laboratory or a satellite experiment is to be intimidated by "fences" and platforms that can be elevated 320 m or tracks that are many kilometers long. However, these items are not at all unusual to the transportation and building construction industries. If a lunar base is developed, the necessary tools are likely to already be present. Furthermore, the problem of constructing tall fences and high elevators is eased by the low lunar gravity.

The preceding example is merely illustrative of many possibilities for achieving higher angular resolution with long-baseline observatories on the lunar surface. A narrow field of view, multiple-pinhole camera or Fresnel zone plates are other possibilities. A large high-energy gamma-ray telescope, for example, an expanded version of the EGRET instrument of the Gamma-Ray Observatory (ref. 5) and a telescope under study for the Space Shuttle external tank (ref. 6) can function extremely well in the vacuum and the weak magnetic field of the Moon. A gamma ray is converted into an electron-positron pair, which then travels in straight lines for long distances. The coordinates along their paths can be detected in spark or proportional chambers to define the incident gamma-ray direction with excellent precision. This is perhaps the only possibility for obtaining the precise positions needed for optical identification of high-energy gamma-ray sources near the galactic equator.

The third general class of instrument is an "all-sky detector." Within the next decade, a great deal of additional information on the temporal behavior of many x-ray objects is expected from Japan's ASTRO-C and the U.S. X-ray Timing Explorer (XTE) satellites. The ultimate instrument is one that combines the resolution of the small-area wide-field cameras of these satellites with the throughput of their large-area detectors, which have small fields of view. The instrument should be capable of resolving thousands of objects simultaneously and providing 10^4 cm^2 of effective area for studying the temporal behavior of many objects without problems of excessive background or source confusion. An example of such an instrument for x-rays is shown in figure 4. It is based on concepts proposed by W. Schmidt (ref. 7) of the Max-Planck Institute and on the "lobster eye" camera of R. Angel (ref. 8) of the Stewart Observatory. This particular device is a hybrid in that it images in one dimension by focusing, whereas a circumferential, pseudorandom collimator with open bands along the axis of the cylinder acts as a coded aperture for angular resolution in the other dimension (ref. 9).

Because individual photons are being detected from thousands of sources simultaneously with their position, energy, and arrival time information encoded to high precision, the quantity of data flowing from the instrument is enormous. A dedicated supercomputer would be needed for processing this data stream in real time and for extracting the essential results. Information on transient events is needed with minimum delay so that it can be transmitted to other observers. Indeed, the coordinates of a given object are needed at the lunar base so that other detectors, including optical and ultraviolet telescopes, can be pointed at a source which is exhibiting gamma-ray or x-ray activity.

Conclusions

A lunar base is the optimum locale for the deployment of the ultimate high-throughput x-ray and gamma-ray instruments. The virtually unlimited space would permit the construction of telescope systems with a collecting area that is, at least, two orders of magnitude more than that of observatories currently in the planning stages for Earth orbit. A stable, very long baseline will also enable achievement of better angular resolution than is currently possible.

References

1. Gorenstein, P.: New Instrumentation for Space Astronomy, K. van der Hucht and G. S. Vaiana, eds., Pergamon Press (Oxford and New York), 1978, p. 237.

2. Gursky, H., et al.: Astrophys. J., vol. 223, 1978, p. 973.

3. Schwartz, D. H.; Schwarz, J.; Gursky, H.; Bradt, H.; and Doxsey, R.: Proceedings AIAA 16th Aerospace Sciences Conference, 1978, p. 78.

4. Oda, M.: Institute of Space and Astronomical Science Research Note 186, presented at COSPAR/IAU Symposium, Advanced Space Instrumentation in Astronomy, 1982.

5. Hughes, E. B., et al.: IEEE Trans. Nucl. Sci., vol. NS-27, 1980, p. 364.

6. Koch, D.: Proceedings of the 19th International Cosmic Ray Conference, NASA CP-2376, Aug. 1985.

7. Schmidt, W. K. H.: Nucl. Instrum. Methods, vol. 127, 1975, p. 285.

8. Angel, J. R. P.: Astrophys. J., vol. 224, 1979, p. 233.

9. Gorenstein, P.; and Mauche, C.: High Energy Transients in Astrophysics, AIP Conference Proceedings no. 115, S. E. Woosley, ed., American Institute of Physics Press, 1984, p. 694.

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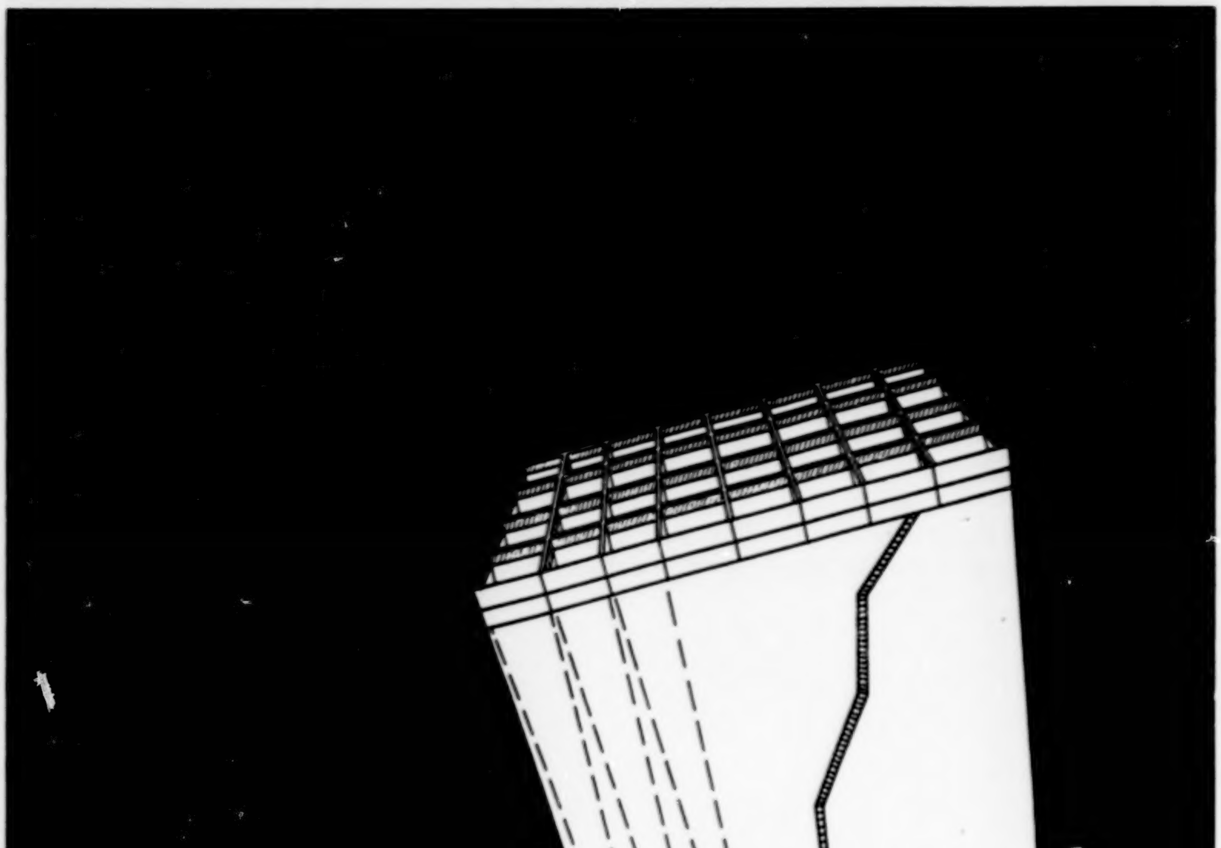

Figure 1.- Artist's conception of a lunar-based LAMAR. As the Moon rotates, sources are maintained within the telescope fields of view by a pointing system. The collecting area of a lunar-based facility can be much greater than those of the next generation of Earth-orbiting x-ray and gamma-ray telescopes.

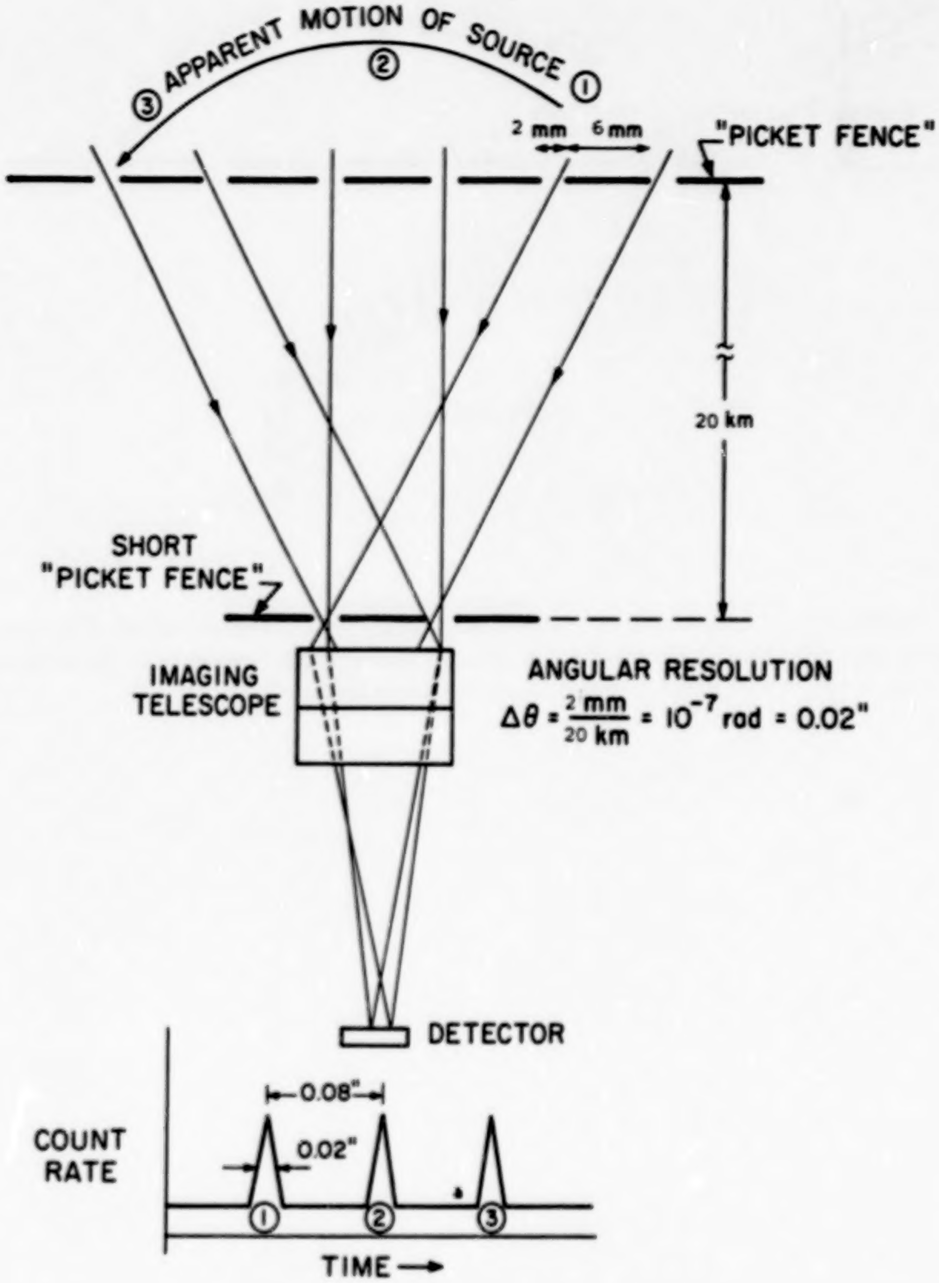
③ APPARENT MOTION OF SOURCE ①
②
2 mm
6 mm
"PICKET FENCE"
20 km
SHORT "PICKET FENCE"
IMAGING TELESCOPE
ANGULAR RESOLUTION
$\Delta\theta = \frac{2\text{ mm}}{20\text{ km}} = 10^{-7}$ rad = 0.02"
DETECTOR
COUNT RATE
0.08"
0.02"
①
②
③
TIME →

Figure 2.- Plan view of long-baseline system with very high angular resolution. Because flux transmitted through two "picket fence" collimators is modulated by lunar rotation, x-rays having wavelengths of 0.4 nm or less are not diffracted significantly. Deconvolution of the modulations reveals the structure of the source in one dimension to a resolution of 0.02 arcsec or less. This resolution is far better than can be achieved by conventional x-ray telescopes Synchronized rotation of the two collimators about a common axis could, in principle, provide imaging information in two dimensions.

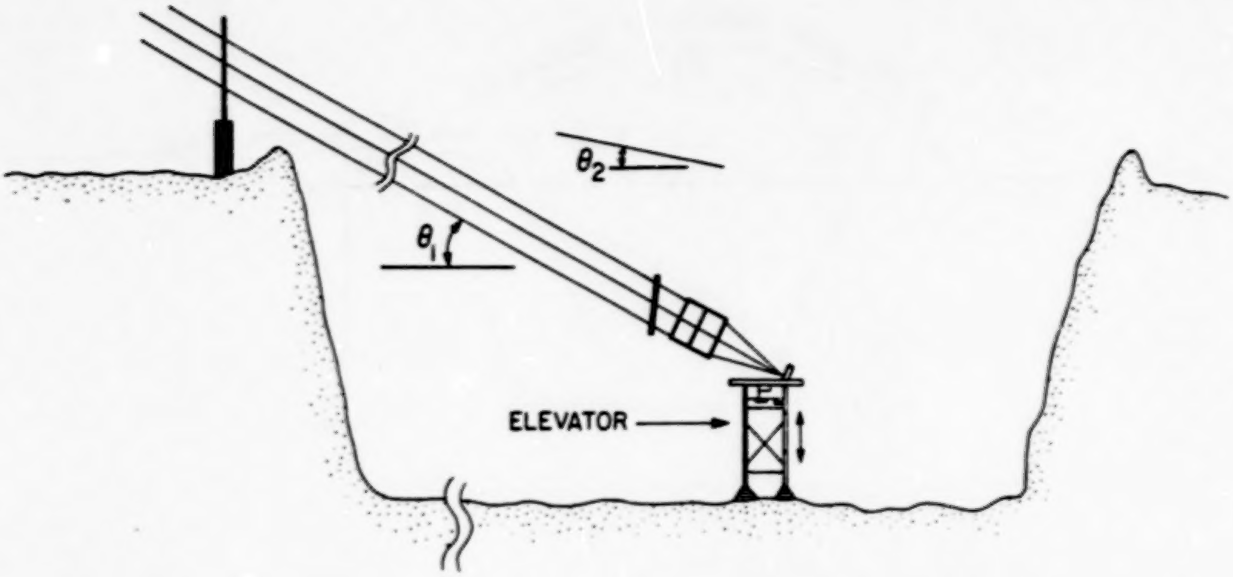

Figure 3.- Profile view of long-baseline system shown in figure 2. The elevation of the second collimator (short "picket fence") and the detector is varied with respect to the floor of a crater so as to remain pointed at a source as it rises or sets between angles θ_1 and θ_2.

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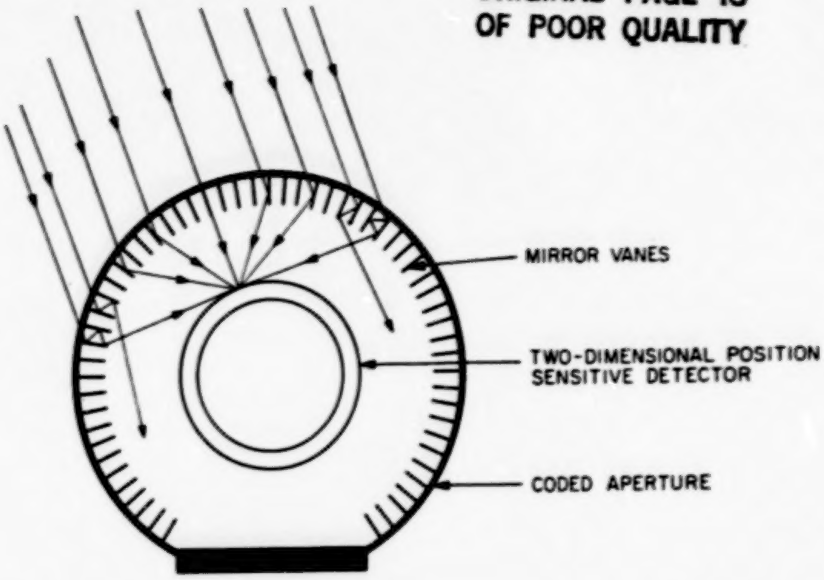
MIRROR VANES
TWO-DIMENSIONAL POSITION SENSITIVE DETECTOR
CODED APERTURE

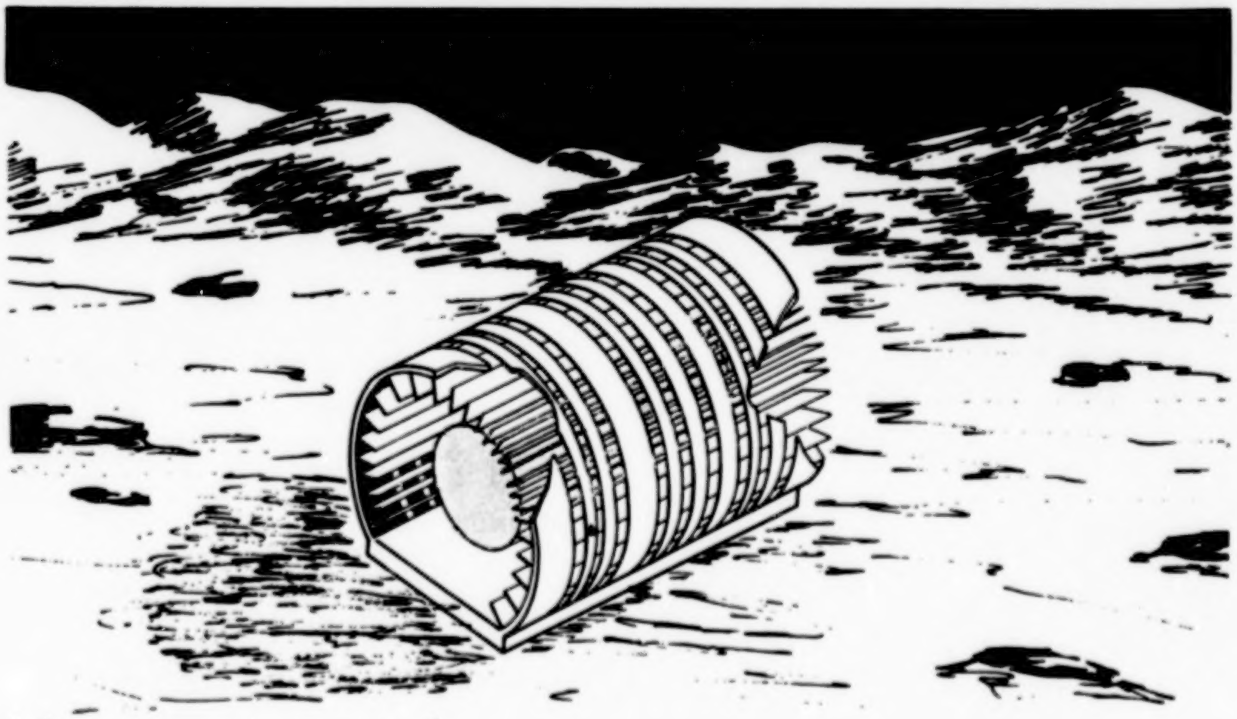

Figure 4.- A large-area, wide-field x-ray camera system fixed on the lunar surface. The camera focuses in one dimension, as described in reference 7, and has a coded aperture for angular resolution in the other dimension. This instrument is capable of monitoring temporal variations of many sources simultaneously. The maximum angle of reflection, actually about 1°, appears greatly exaggerated in the figure.

N89-15817

COSMIC-RAY DETECTORS ON THE MOON

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The Place of Cosmic-Ray Studies in Astronomy

In the context of astronomy, cosmic rays are charged particles – usually protons or electrons – that have been accelerated through the action of naturally occurring electric fields, or they are neutral secondaries of such particles. Presumably, the electric fields are a consequence of changing magnetic fields. The high energy of the particles shows that these fields are remarkably strong and extensive. Cosmic rays provide direct and conclusive evidence that particle acceleration is a ubiquitous and energetically very important feature of the astronomical landscape, which increases in importance as one leaves the familiar territory inhabited by ordinary stars to explore the extreme conditions present in supernova explosions, near collapsed stars, and near active galactic nuclei.

Although the cosmic rays studied directly near the Earth are almost all protons or other nuclei until recently, the indirect evidence for cosmic rays in distant parts of the universe has shown only that high-energy electrons are present. This evidence comes from synchrotron radiation. Analogous evidence for the presence of high-energy nuclei, hence for the fields that have accelerated them, is given by gamma rays and neutrinos arising from the decay of pions produced in hadronic interactions.

Cosmic rays also provide the only directly accessible sample of matter from outside the solar system. Since they can travel very great distances, they may reveal the existence of mirror-image galaxies consisting entirely of antimatter. Carbon-14 and other "cosmogenic" nuclides provide information about the activity of the Sun in prehistoric times, whereas, on shorter time scales, cosmic-ray modulation is an important source of information about conditions in the heliosphere far from the ecliptic plane.

The Scale and Character of Cosmic-Ray Research

The current scale and character of worldwide cosmic-ray research is shown in table I in the form of a program summary of the Nineteenth International Cosmic Ray Conference, which took place in La Jolla, California, in the summer of 1985. These conferences have been held every 2 years since the first one in Kracow, Poland, in 1947. Like most conferences, they have grown, so that the attendance has been about 500 in recent years. The number of contributed papers has been about 1000; thus, even with a limit of 4 pages each, one is faced every 2 years with 10 or more thick volumes of conference proceedings. The number of professional scientists engaged in this work is about 1000. This number may be compared to Virginia Trimble's estimate that, currently, there are about 7000 professional astronomers worldwide.

In 1985, about one-fourth of the sessions (those listed under "High-energy interactions") concerned the application of cosmic rays to the study of particle physics rather than astronomy. Some of this activity, but not all, will dry up in the next few decades because of competition from manmade accelerators (colliding beam machines). A large percentage of the papers (almost 80%) concerned observations (called "experiments" in this context) and the manner of performing them.

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Advantages and Disadvantages of the Moon as a Base for Cosmic-Ray Observations

Advantages

Some advantages of the lunar surface as a location for performing cosmic-ray observations follow.

1. Absence of atmosphere

2. Weak magnetic field

3. Low radiation background

4. Vast extent

5. Enormous mass, for use as shielding, as target material, in construction, and as raw material for manufacturing

6. Stability

7. Low gravity

8. High vacuum

9. Variety of environments (within a small range) by choice of latitude

The absence of an atmosphere has overwhelming importance. As humans, we tend to take for granted the atmosphere on planet Earth. We overlook the fact that its transparency to very-low-energy electromagnetic quanta is exceptional, a consequence of the capability of these quanta to propagate through the atmosphere in the form of waves. However, to higher energy electromagnetic quanta and to fast particles, our atmosphere is a formidable barrier; at sea level, it is equivalent to 33 feet of water. All the cosmic rays one observes at the Earth's surface consist of secondary particles, a greatly altered remnant of those striking its atmosphere from above.

Another form of shielding is provided by the Earth's magnetic field. Except near the geomagnetic poles, this field prevents charged particles from reaching the Earth's surface unless their energy is higher than 1 to 10 GeV, three orders of magnitude above the energy of charged particles produced by radioactivity.

It follows that, with a few notable exceptions, observations of primary cosmic rays must be performed currently using balloons, rockets, or space vehicles. Thus, for the majority of observations listed in table I, the Moon is an excellent site. The exceptions include, of course, some of the solar and heliospheric observations requiring special locations in the solar system. The other exceptions are observations of nuclei, gamma rays, neutrinos, and interactions of these particles, in the highest energy range, for which the Earth's atmosphere is used as an amplifying device in the production of extensive air showers.

In a number of cases, the Moon is not just an alternative to artificial satellites. Its other advantages – of vast extent, enormous mass, and low level of background radiation – will enable performing cosmic-ray observations on the Moon that otherwise would be physically impossible or economically impractical. One of these cases, neutrino astronomy, has been described in another paper; others are described in the final portion of this paper, following some comments about scientific style and its possible implications with respect to cosmic-ray detectors on the Moon.

Disadvantages

Some disadvantages of the lunar surface as a base for performing cosmic-ray observations are the high cost of transport from Earth and the absence of an atmosphere and of oceans.

The Scientific Backdrop

Since they first began, cosmic-ray studies have manifested a special style which may still influence the manner in which cosmic-ray physicists react to opportunities afforded by the establishment of permanent bases on the Moon. Cosmic rays were discovered not in the laboratory but at great heights by placing ionization chambers in manned balloons (Hess 1912). The extraordinary penetrating power that distinguishes cosmic rays from other forms of natural radiation was demonstrated not in the laboratory but by lowering ionization chambers to suitable depths in mountain lakes at different altitudes in the California Sierras (Millikan 1923-26). Proof that primary cosmic rays are mostly charged particles (Clay 1928-33, A. H. Compton 1930-36) and that their charge is positive (T. H. Johnson, L. Alvarez, Rossi and DeBenedetti 1933) was obtained not in the laboratory but by using the Earth's magnetic field, observing first the latitude effect and then the east-west effect. Proof that cosmic-ray energies can measure at least 10^{15} eV (Auger et al. 1938) depended on the fact that particles with this much energy generate enormous atmospheric cascades, called extensive air showers. Considering just the solid angle, any air shower experiment at sea level makes essential use of a cone-shaped chunk of atmosphere weighing some 10^{10} kg. This mass explains why the lack of an atmosphere can be a disadvantage for locating cosmic-ray detectors on the Moon.

The greatest contribution of cosmic-ray studies to science came from discoveries leading to a new branch of physics, particle physics, now performed almost entirely using giant particle accelerating machines. Some of these discoveries, of the positron, of μ-mesons or muons, of charged π-mesons or pions, of kaons, and of hyperons, were made in a conventional laboratory setting. Others involved going out of conventional laboratories and setting up unique new bases on the highest accessible mountains: on Mt. Evans in the United States, on the Jungfraujoch, Aiguille du Midi, and Testa Grigia in the Alps, on Chacaltaya in Bolivia, and in the Pamirs of central Asia. Going to the other extreme, the discovery of cosmic neutrinos was made using the deepest accessible mines, at Kolar Gold Field in India and in South Africa.

These accomplishments illustrate a certain scientific style. The physicists who performed these feats were equipped with an especially broad range of knowledge and skills. But they also were marvelously opportunistic, using whatever was available in the environment, and later on, using whatever new vehicles were introduced to gain access to new environments. The discovery of the Van Allen radiation belts was the first discovery using a space vehicle. There are important cosmic-ray detectors still functioning on the Explorer spacecraft, which are now reaching the boundary of interplanetary space.

The important advantages offered by the Moon no doubt will be exploited for the study of cosmic rays. However, this opportunistic style makes it hard to predict the form of cosmic-ray detectors on the Moon. Most of the earliest detectors will be similar to instruments already in use. Others will take advantage of unrelated activities in progress on the Moon at later times. Planners should be warned, perhaps, that cosmic-ray scientists are used to not paying for some essential parts of their equipment such as mountains, mines, or the overlying atmosphere. Planners must guess first what other investigators will be doing and then make guesses about how cosmic-ray scientists might avail themselves of the new research environment. Some of these guesses follow.

Cosmic-Ray Detectors on the Moon

Most studies of solar and heliospheric cosmic rays and of cosmic-ray phenomena require long-term observations using relatively small, lightweight detectors. Studies of gamma-ray bursts are similar in this regard. The lunar surface is an attractive location for work in these fields, but there is no obvious way to enhance the value of this work through the application of lunar resources.

The kind of cosmic-ray research that is likely to be performed on the Moon in the early stages of lunar base development is research in the low-energy range on constituents such as ultraheavy nuclei, positrons and electrons, gamma rays, antiprotons and antinuclei, and certain secondary isotopes useful as cosmic-ray clocks. These constituents share the property of being very sparse; therefore, detectors need to be very large, although they can be lightweight in relation to size. The detectors are well suited to modular design and for incremental assembly. By basing detectors of this kind on the Moon rather than on a space station, money may be saved in the areas of deployment, mechanical support, and some aspects of maintenance.

At higher energies, the intensity decreases; thus, the need for large detectors becomes even greater. It also becomes difficult to measure the energy of the particles and to differentiate between particles. As a rule, a target of some kind in which the particles undergo collisions with stationary nuclei must be provided. The detector must be very heavy and very large. Since unprocessed lunar soil is entirely adequate for use as a target and an absorber, the Moon has an overwhelming advantage over space stations as a base for detectors of every sort of very-high-energy (VHE) cosmic rays.

Illustrative Examples

Figure 1 shows the manner in which a detector of high-energy (greater than 1 TeV) gamma rays, electrons, and charge-resolved nuclei might be incorporated in the protective shield of a structure intended primarily for manufacturing or research of some kind unrelated to cosmic rays. The structure is imagined to be roughly cylindrical, 20 m in diameter and 50 m long. For the protection of personnel from the intense low-energy cosmic rays, it has been shielded with a 5-m-thick layer of lunar soil. I have imagined that during construction of the shield, several layers of lightweight gas-filled counters were deployed at intermediate depths. A similar layer of counters lies on top of the shield, and a final layer is attached on the inside to the ceiling of the tank.

The uppermost layer of counters measures the charge of individual incoming particles. The first layer of soil beneath it acts as a target in which the particles initiate cascades. The higher the incident energy, the larger the cascades will be and the further they will penetrate. The number of particles reaching successive layers of counters provides a measure of the primary energy and also serves to discriminate between incident hadrons (nuclei) and leptons (electrons) or gamma rays.

The product of detection area and solid angle is several thousand m^2-steradians; thus, the cosmic-ray counting rate will be several thousand per year for particles with an energy greater than 10^{16} eV. Useful results on cosmic-ray composition will be obtained to a maximum energy of 10^{17} eV per particle, the energy spectrum of electrons will be measured up to about 10^{14} eV, and gamma rays from point sources will be observed up to at least 10^{14} eV.

Lightweight counters can be constructed from metallized plastic foil as indicated in figure 2, and the cylindrical shape of the individual cells is maintained by the pressure of the filling gas. The tendency for distortion produced by the pressure of the overlying soil is reduced by the low gravity of the Moon, so the filling pressure does not have to be excessively great. Perhaps the filling gas, typically consisting mainly of argon, can be obtained as a byproduct of the gas extraction plants some authors have envisioned for generating hydrogen on the Moon.

Another interesting possibility is to measure the intensity of ultra-high-energy (UHE) antiprotons, using the Earth's magnetic field to separate them from the much more abundant protons. Antinuclei accelerated in antigalaxies, if they exist, can enter the Milky Way galaxy more easily if their energy is ultrahigh. To accomplish the separation, one would use a horizontal cosmic-ray telescope located near the Moon's limb so as to point at all times in the direction of the Earth.

In general, highly relativistic particles with a charge Z times the charge of an electron, and energy E (electronvolts), will be deflected by a transverse magnetic field $B_\perp$ (gauss) through an angle θ given by

$$\theta = \frac{300Z}{E} \int B_\perp \, ds$$

where the integration is over the path of the particle. For particles grazing the Earth's limb in the equatorial plane, the magnetic field integral equals 4×10^8 G-cm, some 400 times greater than the field integral of a superconducting magnet facility proposed for the U.S. Space Station. The energy coverage would therefore extend to energies that are higher by about the same factor.

A consequence of this deflection is that the Earth's cosmic-ray shadow, due to particles being intercepted by the Earth, will be displaced through an angle given by the equation. For a given particle energy, the shadows produced by protons and antiprotons will fall symmetrically on opposite sides of the geometrical shadow.

The telescope I envision, shown schematically in figure 3, would consist of a large ionization calorimeter for measuring E and of widely spaced drift chambers for finding particle trajectories. The ionization chamber would consist of gas-filled counters interleaved with bins of lunar soil. Electrons and antiprotons of the same energy would be distinguishable by virtue of their different cascade profiles; electron-initiated cascades are purely electromagnetic, whereas cascades initiated by antiprotons are hadronic. The calorimeter would be used concurrently, in combination with other counters not shown here, for other purposes, such as gamma-ray astronomy in the VHE-UHE bands.

TABLE I.- PROGRAM OF THE 19TH INTERNATIONAL COSMIC RAY CONFERENCE, LA JOLLA, CALIFORNIA, AUGUST 11-23, 1985

[Numbers of sessions devoted to the various topics]

GALACTIC AND EXTRAGALACTIC COSMIC RAYS			37
Observations		24	
Gamma rays	11		
Nuclei	9		
Electrons, positrons, antiprotons	2		
Neutrinos	1		
Searches for monopoles, quarks, etc.	1		
Theory		7	
Techniques and Instrumentation		6	
SOLAR AND HELIOSPHERIC COSMIC RAYS AND COSMIC-RAY PHENOMENA			21
Observations		16	
Solar flare particles and gamma rays	4		
Solar neutrinos	1		
Interplanetary acceleration, Jovian electrons	1		
Modulation	7		
Intensity gradients in the heliosphere	2		
Cosmogenic nuclides	1		
Theory		4	
Techniques and Instrumentation		1	
HIGH-ENERGY INTERACTIONS			18
Observations		10	
Hadronic interactions	5		
Cascades	3		
Secondary leptons (muons) and leptonic interactions	2		
Theory and Simulations		5	
Techniques and Instrumentation		3	

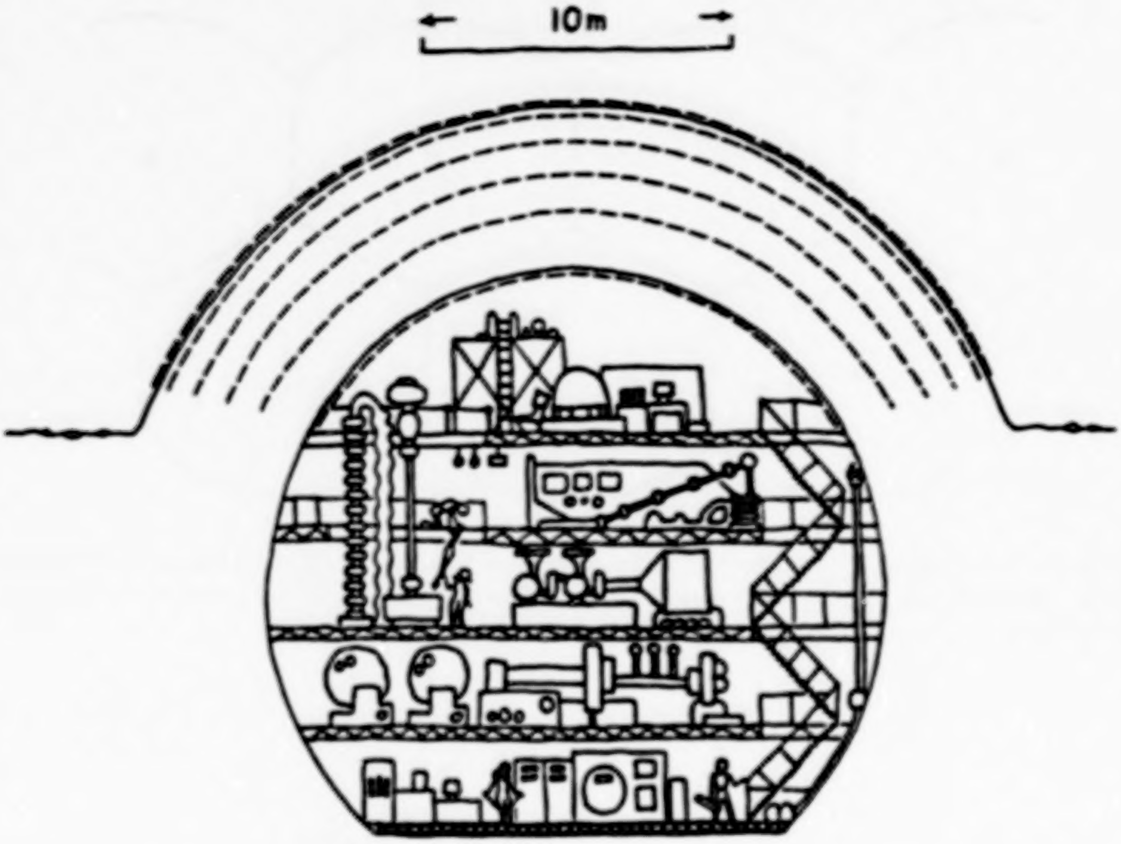


Figure 1.- A large ionization calorimeter built into the shielding of a manufacturing facility or a laboratory on the Moon. The dashed lines represent layers of gas-filled ionization counters.

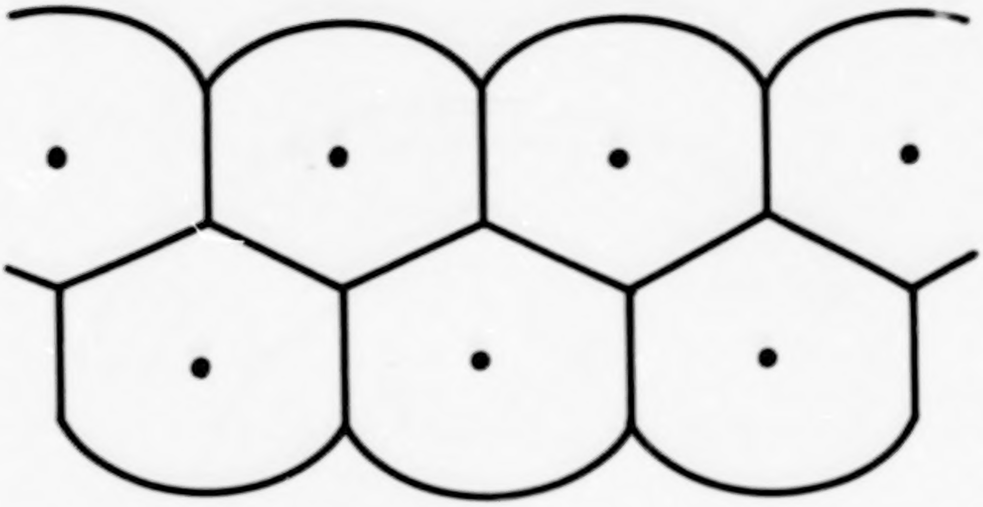
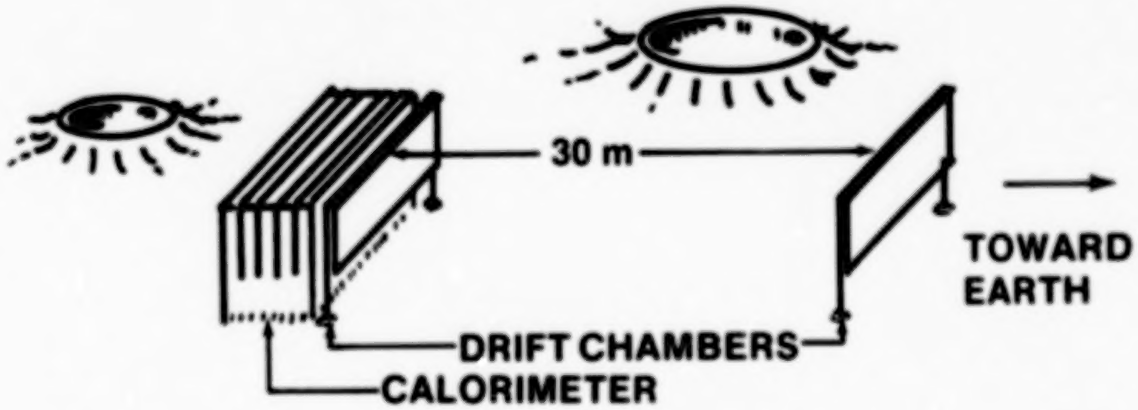


Figure 2.- Cross section of a lightweight gas counter panel made of metallized plastic foil (with the usual anode wires). To save cargo space, the panels would be deflated and pressed flat during shipment.



30 m
TOWARD EARTH
DRIFT CHAMBERS
CALORIMETER

Figure 3.- A cosmic-ray charge analyzer designed to be located on the Moon and to use the Earth's dipole as a magnet.

N89-15818

SPACE AND LUNAR-BASED OPTICAL TELESCOPES

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The Great Observatory Program

The Great Observatory Program indicates a commitment by NASA and, I hope, by this Nation to support permanent major capabilities in space covering much of the electromagnetic spectrum. The well-known five major observatories are Hubble Space Telescope (HST), Gamma-Ray Observatory (GRO), Advanced X-Ray Astrophysics Facility (AXAF), Space Infrared Telescope Facility (SIRTF), and Solar Optical Telescope (SOT). All are relatively general purpose astronomical facilities, tailored to a given spectral region or, in the case of SOT, to solar observations. The HST, the AXAF, and the SIRTF are intended to be long-lived satellites; therefore, their large development costs can be amortized over 10- to 15-year lifetimes.

In addition to the budgetary benefits, maintenance of these satellites by the Space Shuttle and the Space Station will provide important scientific benefits: the continuity of national and individual science programs, the use of replenishable cryogenics on all three satellites, and maintained excellence through the upgrading of the scientific instruments. These qualities are valuable and should not be dismissed lightly. Just as valuable but more difficult to quantify are the multiplicative benefits provided by the scope of the overall program.

1. The temporal overlap with the other space observatories will provide for rapid followup in multiple bands.

2. The long-term nature of the observatories permits both short-term and long-term programs along a broad front of scientific objectives.

3. Ultimately, these observatories will lead to increased discipline-crossing, coordination, and scientific integration with ground facilities. This progression is extremely valuable for both the scientific spinoffs and the sharing of technological advances.

Thus, although there is an equal need for unique and innovative programs to solve critical scientific problems, the long-term access to general-purpose space observatories holds a great future for astronomy and science in general. Indeed, one of the major attractions of a lunar base for astronomy is the continuation and expansion of the Great Observatory Program. The long-term use of each observatory and continuity within the program are two goals addressed in the timetable and the remarks that follow.

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[1] Operated by the Association of Universities for Research in Astronomy, Inc., for the National Aeronautics and Space Administration.

The Next 25 Years

An optimistic timetable for reaching various milestones in the development of astronomical facilities is presented in table I. The approximate years of launch are indicated for the Great Observatories, the Space Station, and an orbital transfer vehicle. Dates are estimated for the launch of optical, infrared, and x-ray observatories. Because each of these observatories is assigned a 15-year lifetime, the launch date given on the timetable for the second generation of these observatories is 15 years later. It is clear from such a schedule that the second-generation space telescope will be needed a decade before the construction of the required far-side base. Indeed, planning for the HST replacement should begin within the next 3 to 4 years.

Possible Successors to the Hubble Space Telescope

The approach Bely (Space Telescope Science Institute) and Roddier (National Optical Astronomy Observatories) have taken in a recent paper is to compare the relative scientific benefits and maturity of designs proposed for the spectral region covered by the HST, with consideration given to effective collecting area and angular resolution. The effective collecting area and the angular resolution for a 4-m-class ground-based telescope, for the HST, and for satellite instruments with a variety of effective filling factors are shown in figure 1. Near the line given by a completely filled single disk is an 8-m disk proposed by Perkin-Elmer (P-E 8-m) in a recent study done for NASA. Plotted nearby is the Space Ten-Meter Telescope (STMT), a 10-m monolith described later. Appearing somewhat farther from this line are the partly filled interferometric arrays, COSMIC 1 and COSMIC 4, proposed by Traub and the nonredundant Golay designs also studied by Perkin-Elmer. At much higher resolution, but with considerably less collecting area, the free-flying, kilometer-baseline spacecraft couples such as TRIO, proposed by Labeyrie, can be found.

The considerably broader angular field, the ability to use conventional spectroscopic and imaging instrumentation, and the considerably enhanced collecting area support the selection of a filled-aperture approach for the next-generation, general observatory in the ultraviolet/near-infrared region. Further, the low-risk simplicity of operation and design of a filled array may well compensate for much or all of the increased costs suggested by typical scaling laws. However, the appropriate scientific weighting of these factors will be much better understood following the analysis of early space telescope data and, in particular, the work on complex stellar fields and distant sources.

The Space Ten-Meter Telescope

The Bely and Roddier design has as its goal a general-purpose observatory, supporting both imaging and spectroscopy, with a significant gain in collecting power and resolution compared to the HST. Like the HST, it will cover the ultraviolet portion of the spectrum to the midinfrared. It will be limited by mirror coatings and polish to a low wavelength near 120 nm and by thermal mirror emissivity to the 4- to 5-μm range, with good collecting power for bright sources to 10 to 20 μm. One crucial feature is the use of geosynchronous orbit, which yields very high operational efficiency and simplicity as demonstrated by the successful International Ultraviolet Explorer.

A cross section of the satellite displayed in figure 2 shows its most salient features.

- The fast f/1 primary mirror made from glass or ceramic is diffraction-limited in the 0.6- to 1.0-μm wavelength range.

- Because of "g" release concerns and the potential for large temperature differentials across the primary, the secondary mirror will be actively controlled on time scales of hours.

- The ultimate in resolution for the ultraviolet can be achieved by using interferometric techniques over a narrow field as suggested by Roddier.

- Because of the fast primary mirror and the distance to the Earth, the baffle can be kept very short yet still achieve negligible scattered light background.

- The baffle and the primary and secondary mirrors are passively cooled to 170 K in the same fashion as the large deployable reflector (LDR).

Given optimum enabling technologies, the telescope's performance would be spectacular. The STMT would have

1. Four times the resolution of the HST: 20-marcsec images in the visible

2. Sixteen times the light gathering power of the HST

3. A limiting magnitude in the visible wavelength for a 3-hour exposure of a 33rd magnitude star (an A star in Virgo)

4. Excellent performance out to 4 μm, where the collecting power and angular resolution will complement SIRTF and the next-generation cryogenically cooled telescope in the same way that LDR complements SIRTF on the long-wavelength side

The Advantages of Earth Orbit and Lunar Sites

Some of the key advantages of the Space Ten-Meter Telescope are provided or enabled by a high Earth orbit. A review of the various qualities of low Earth orbit (LEO), geosynchronous orbit (GEO), and lunar siting (table II) reveals some of the major issues which will determine the manner in which a lunar base will continue the development and maintenance of permanent ultraviolet-optical astronomical facilities.

Launch and Building Costs

Launch and building costs for lunar-based facilities certainly will determine the nature of the first optical telescopes. If site preparation and construction costs are very high, then the first astronomical facilities are likely to be largely preassembled and capable of standalone operation. These could be small-diameter, Explorer-class telescopes mounted in support stations similar to the lunar or Mars landers. Examples of these could be astrometric telescopes, all-sky ultraviolet-optical survey telescopes, and solar stellar monitors. An exciting prospect is that the initial restriction to small sizes would still permit the construction of unique very-large-array optical facilities in the early years of a lunar base. To ensure that the cost of site preparation and construction of the prefabricated observatory will be small relative to ongoing expansion and utilization of the lunar base, large, 10-m-class telescopes probably will be constructed after the lunar base population has increased significantly.

Low Light Backgrounds

For both small and large telescopes, the lunar basing offers extremely low light backgrounds for the majority of the orbit. To avoid scattered light from earthshine, the optical site should be placed on the equatorial limb or preferably on the far side. To avoid manmade light pollution, the site should be placed approximately a kilometer from any lighted manned base.

Maintenance and Refurbishment

A major drawback of a geosynchronous orbit is the cost and difficulty of maintenance and refurbishment from the Space Station. Once a lunar base is self-sufficient in propellant manufacture, one of the early benefits of a lunar base may be servicing of geosynchronous satellites such as the STMT.

STMT Designs for a Lunar Base

The single monolith telescope which is suitable for geosynchronous orbit would need major changes for a lunar site. First, the finite gravity would deform even the 10-ton single dish. Instead, the lunar analog would probably be a segmented mirror, constructed on the Moon , with a significantly larger diameter, say 25 m. Control of each segment in the fashion of the Keck telescope would be possible and would yield the largest optimum field of view. Given the slow rotation of the Moon, the tracking might be done by secondary control, interspersed with motions of the entire dish.

Thermal Effects

The use of passive cooling would be desirable in order to push as far as possible into the near-infrared. However, temperatures much less than 170 K may be difficult to achieve. Although mirror deformations caused by thermal effects would be removed by the segment actuators, it is clear that thermal effects will probably be the equivalent of Earth "seeing" at the highest angular resolutions, whereas tracking irregularities will replace the wind buffeting as the cause of pointing instability. To better stabilize the thermal environment, the telescope should be housed in a large, insulated enclosure for the daylight period. With the use of a movable sunshade outside the "dome" and a radiation screen in the "slit," a portion of the daylight period could be used for continued observation and work in the solar-blind portion of the spectrum (120 to 200 nm).

Instrument Selection

Another advantage of a permanent, lunar-based optical facility compared to a free-flying satellite would be the ability to upgrade scientific instrumentation and provide for more flexible configurations such as optics customized for particular wavelength regions and more special-purpose instrumentation. One of the serious drawbacks of current space astronomy has been called the "Tyranny of the Masses," which means that special-purpose or complex instrumentation such as polarimeters, multiobject spectrographs, narrow-band imagers, and astrometric devices are at a disadvantage in competition for limited focal plane and satellite resources. With the possibility of weekly or monthly configuration changes, these unique instruments can be used to full advantage. Therefore, it is highly desirable for a filled-dish observatory to have the capability for monthly configuration changes, which are usually accomplished during the daylight period.

Data Handling

Optical astronomy is being inundated with high-volume, digital data. The Space Telescope Data Capture Facility was designed to accommodate 2 × 10^9 bits per day and will no doubt be saturated, particularly with the second-generation spectrograph. The STMT described earlier and a lunar version would have a usable focal plane of 2 × 10^8 pixels, and detector arrays of this size should be available. For read periods of 10^3 seconds, the data flow would be 3 × 10^{11} bits per day, or greater than the capacity of a 3-MHz dedicated link. Although operation of the telescope would probably be handled at a remote base with data telemetered to Earth for reduction, lunar-based operators must have a quick-look capability and limited data reduction tools to enable verifying proper operation. On the basis of HST experience, it is clear that computational capabilities comparable to a current supercomputer will be required (10 to 20 megaflops).

Conclusion

These observations have been limited to an extrapolation of HST capabilities in terms of a large, passively cooled, single-disk telescope, which will be required to continue the progress of ultraviolet to near-infrared astronomy well beyond the lifetime of the HST. On the Moon, many of the operational advantages of ground-based astronomy will permit novel instrumentation and new advances in the region of the spectrum best suited for the studies of stars and stellar systems. However, the Moon holds even greater advantages for spectacular improvements over the traditional observatory, particularly in the areas of long-baseline optical interferometry and large, cryogenically cooled telescopes.

TABLE I.- CURRENT TIMETABLE FOR THE GREAT OBSERVATORIES

Date	Event
1986*	Hubble Space Telescope launch
	Gamma-Ray Observatory launch
1990	Hubble Space Telescope refurbishment
	Space Station started
	Advanced X-Ray Astrophysics Facility launch
	First Hubble Space Telescope advanced scientific instruments (ASI)
	Space Station completed
	Space Infrared Telescope Facility launch
1995	Second Hubble Space Telescope ASI
	Geosynchronous orbit transfer vehicle available
2000	
	First lunar base established
	Space Ten-Meter Telescope launch/large deployable reflector launch
	Gamma-Ray Observatory II launch
2005	
	Advanced X-Ray Astrophysics Facility II launch
2010	Space Infrared Telescope Facility II launch
	Far-side lunar base established
2015	First large lunar telescopes

*Editor's note: These dates represent pre-*Challenger* schedules. As of this writing, the HST is manifested for a 1989 launch. Uncertainties in the Space Shuttle schedule, in Space Station deployment, and in further development of the Great Observatory concept will change this qualitative plan further. (W. W. M.)

TABLE II.- ADVANTAGES OF VARIOUS SPACE LOCATIONS FOR ASTRONOMICAL FACILITIES

Characteristic	LEO	GEO	Lunar base
Launch costs	Low	High	High
Maintenance platform	STS/SS[a]	SS/LB[b]	LB
Maintainability	Very good	Poor	Very good
Science operations	Complex	Simple	Simple
Scientific efficiency, %	35	90	45
Optical background	Earth/zodiacal	Zodiacal	Zodiacal
Thermal stability	Poor	Very good	Very good
Maximum exposure, hr	0.75	17	336
Large apertures	Limited	Limited	Good potential
Upgrading	Good	Poor	Excellent
Configuration	Rigid	Rigid	Flexible

[a] STS = Space Transportation System; SS = Space Station.

[b] LB = Lunar base.

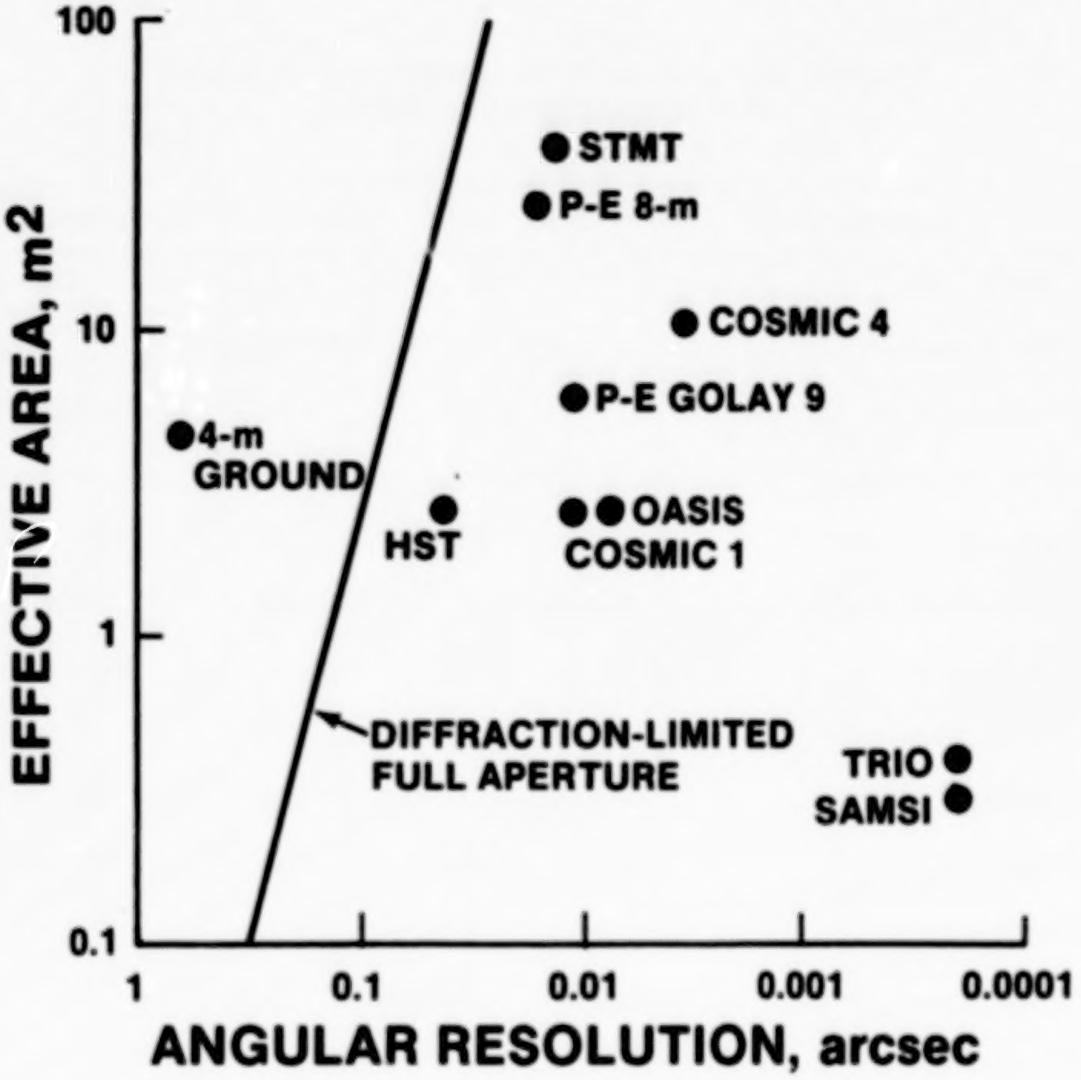
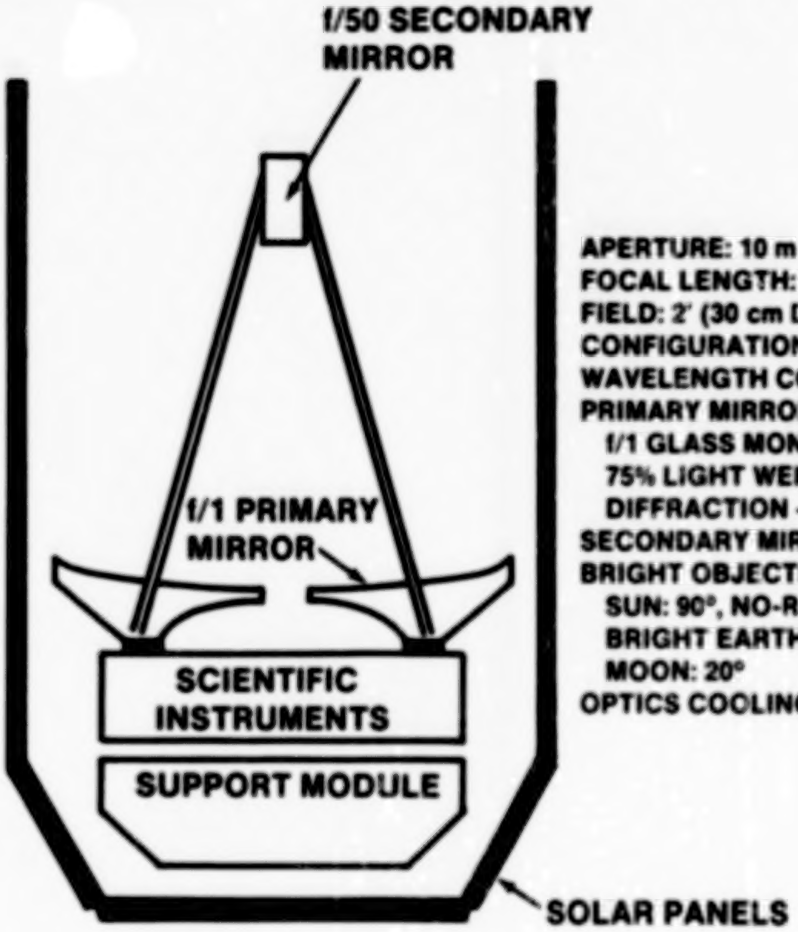


Figure 1.- Effective collecting area as a function of angular resolution for a 4-m-class ground-based telescope, for the Hubble Space Telescope, and for satellite instruments having a variety of effective filling factors. The line represents a completely filled single disk.


f/50 SECONDARY MIRROR
f/1 PRIMARY MIRROR
SCIENTIFIC INSTRUMENTS
SUPPORT MODULE
SOLAR PANELS

APERTURE: 10 m
FOCAL LENGTH: 500 m
FIELD: 2′ (30 cm DIAMETER)
CONFIGURATION: CLASSICAL CASSEGRAIN
WAVELENGTH COVERAGE: 1200 nm TO 30 μm
PRIMARY MIRROR:
  f/1 GLASS MONOLITH
  75% LIGHT WEIGHT
  DIFFRACTION - LIMITED AT 1 μm
SECONDARY MIRROR: ACTIVE
BRIGHT OBJECTS VIEWING LIMITS:
  SUN: 90°, NO-ROLL CONSTRAINT
  BRIGHT EARTH: 60°
  MOON: 20°
OPTICS COOLING: PASSIVE 170 K

Figure 2.- Cross section of Space Ten-Meter Telescope.

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ASTRONOMICAL INTERFEROMETRY ON THE MOON*

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Introduction

Optical interferometric arrays are particularly attractive candidates for a manned lunar base. The radio model already exists in the very large array (VLA) of the National Radio Astronomy Observatory, situated on the plains of St. Augustine near Socorro, New Mexico. A Y-shaped array of 27 antennas, each arm being 20 km long, operates as a coherent array, giving 0.1-arcsec resolution at 2-cm wavelength. An array of similar concept, but with optical elements, would therefore give angular resolution of nearly 1 μarcsec at optical wavelengths and would give an absolutely revolutionary new view of objects in the universe. It would not be built on the Earth's surface, because the atmosphere damages the phase coherence severely at optical wavelengths. It could be constructed in Earth orbit as an assemblage of stationkeeping free-flyers (proposals to do so have been put forward), but the technical problems are not simple (e.g., controlling element position and orientation to 10 nm at 20 km). If a permanent lunar base were available, an optical analog of the VLA would, in contrast, be a relatively straightforward project.

The Case for High Angular Resolution

Galileo's telescope was the first step in improving the angular resolving power of the human eye; this thrust in astronomy continues in our own time. The atmosphere of the Earth has posed a barrier at about 1 arcsec (perhaps one-third of an arcsecond at the best sites), but if optical instruments can be mounted in space, there seem to be few fundamental difficulties in extending to the microarcsecond range. Most of the problems are of a practical nature, centered on structural stability, satellite stationkeeping, instrument adjustment and control, and related technical questions. These problems are solvable in principle, but solutions may be costly if conventional orbital concepts are followed. Although the surface of the Moon has not been seriously considered in the past, it appears that a lunar location would be advantageous for astronomical instruments of great power. A permanently occupied lunar base could be a key factor in such a program.

Angular resolution can never be better than the diffraction limit λ/D, the wavelength divided by the aperture diameter, and at 500 nm, a 1-m aperture gives 0.1-arcsec resolution. Milliarcsecond and microarcsecond resolution will require interferometers of large size, but much wider classes of objects, all of great current interest, become accessible. These are illustrated in figure 1, which shows the approximate optical fluxes and angular sizes of a variety of stellar and extragalactic objects. Since the maximum flux and the largest angular size are indicated, objects in each class will generally fall along the locus indicated by the upward-sloping arrows. An object 10 times more distant than the closest member of its class lies at the tip of the arrow, for the given scale. The figure, therefore, gives the largest expected scale for each class of object.

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For the various classes of stars, Dupree et al. (ref. 1) have commented that measuring the size of a star is not enough. This conclusion is generally valid for nearly all astronomical objects. Most interesting objects tend to be complex, and understanding the physical processes requires some detailed knowledge of the phenomena. For most stars, at least a factor of 30 resolution beyond the gross size is certainly needed (i.e., about 100 pixels). Phenomena such as starspots, flares, and other analogs of solar processes will be interesting and, indeed, should be surprising. One must conclude that every class of stellar object (except for the closest red supergiants) will demand an angular resolution of a milliarcsecond or better.

The extragalactic phenomena are still more demanding. The complexity of the processes is not known, since we do not have close analogs (such as the Sun, for the stellar case) to guide us. The subject matter is of extraordinary interest, however. The physics of quasars, blacertids (extragalactic radio sources), and "ordinary" galactic nuclei are near (or perhaps extend beyond) the limits of fundamental principles. From both radio and x-ray observations of these objects, it is clear that enormous energies are generated, and the indications are very strong that the energy source must be gravitational.

"Black holes," though not yet demonstrated in nature, may be of fundamental importance in these energetic processes. The optical study of the accretion processes and instabilities near the cores of the active extragalactic objects, with high angular resolution, should be as astounding as it has been in the radio case, where milliarcsecond resolution reveals velocities that appear to surpass the speed of light. Figure 1 shows that only the broad-line regions at the nuclei of the closest Seyfert galaxies are accessible to an instrument of milliarcsecond resolution. The rest are smaller in angular size, and it is clear that an optical instrument having angular resolution in the 1- to 10-μarcsec range would have truly extraordinary impact. None of the objects is brighter than the 12th magnitude, and most are substantially fainter; an instrument having at least the collecting area of the Palomar 5-m telescope is indicated. This challenge of obtaining angular resolution in the milliarcsecond to microarcsecond range, with a net collecting area of at least 20 to 30 m^2, is fully justified by the scientific rewards that would surely be gained.

Aperture Synthesis

Radio astronomers have, for the past several decades, circumvented the problem of obtaining high angular resolution by using interferometry, culminating in the concept that is called aperture synthesis. The methods of aperture synthesis were, ironically, developed by Michelson (ref. 2) for measuring the diameters of stars at optical wavelengths, but the Earth's atmosphere hindered their quantitative use. The radio version of Michelson's stellar interferometer is illustrated in figure 2, which shows a pair of radio telescopes simultaneously receiving radiation from a distant source. There is a difference in arrival time, the geometrical time delay Δt_g, determined by the orientation of the source direction relative to the interferometer baseline. There is obviously no chance of interference if Δt_g is larger than the coherence time t_c of the radiation, so a time delay must be inserted to compensate for this difference. Then, if the antennas are fixed and the source drifts through the reception pattern, the product of the received signal amplitudes varies sinusoidally as the signals interfere, alternately constructively and destructively. The primary reception pattern of half-width θ_B, the fringe spacing ϕ_F, and the delay beam ϕ_D are important characteristic angular scales. The analysis is most straightforward if the antennas track the source, when the source is small compared to the primary beam width θ_B. The fringe spacing is determined by the projected baseline D', which is the projection normal to the incoming radiation.

For the interferometer description, there is a third angle, the delay beam ϕ_D, which is determined by the receiving bandwidth or, equivalently, by the coherence time. If the time delay is set to match Δt_g perfectly, the central fringe will have full amplitude, but as the time delay error grows, the interference conditions will be different at the upper and lower ends of the band. The interference effects cancel, and the fringe amplitude diminishes over an angle $\phi_D \sim 1/B\tau_g$, where B is the bandwidth and τ_g is the baseline length measured in light travel time. The number of fringes observed as a consequence is on the order of the inverse of the fractional bandwidth, an effect that has strong consequences for optical interferometry.

Given a two-element Michelson interferometer as illustrated in figure 2, the output is well specified if the following conditions are met: the source under study must be small compared to both the primary resolution θ_B and the delay beam ϕ_D, and the delay compensation must approximate $\Delta\tau_g$ with an accuracy corresponding to a fraction of the fringe angle ϕ_F, or at least the error must be calibrated to that accuracy. The interferometer output is the convolution of its sinusoidal fringe pattern with the source brightness $B(x,y)$, where x,y are angular coordinates on the sky. Therefore, the interferometer output is equal to the Fourier transform $B(u,v)$ of the brightness distribution. The conjugate coordinates (u,v) are defined by the baseline and the source location as shown in figure 2. On a plane normal to the source direction, coordinates (u,v) are defined (north and east, for example) and the interferometer baseline D, measured in wave numbers $(2 \times D/\lambda)$, is projected onto that plane with the reference antenna (which can be chosen arbitrarily) at the coordinate origin. The plane is called the u-v plane, and the projected vector $D'(u,v)$ defines the conjugate coordinates at which the Fourier transform $B(u,v)$ is defined by the fringe amplitude and phase. If all interferometer baseline lengths and orientations are taken, the complete Fourier transform is determined, and performing Fourier inversion gives a true map $B(x,y)$ of the source. In practice, of course, noise is introduced by the apparatus, the coverage of the u-v plane is not complete, and due caution and knowledge must be exercised.

The process by which the Fourier transform is developed is known as aperture synthesis, and substantial literature has been developed for the radio case. The first complete description, in which the rotation of the Earth was used to move the interferometer baseline, was conceived by Ryle and Hewish (ref. 3). An authoritative summary of the two-element interferometer has been given by Rogers (ref. 4). The most powerful aperture-synthesis instrument, the radio array known as the VLA (the very large array, operated by the National Radio Astronomy Observatory), is described by Napier et al. (ref. 5). The VLA probably provides the best model for a desirable optical instrument. Its 27 elements give 351 simultaneous baselines; therefore, "snapshots" of fairly complex objects are nevertheless faithful representations if the target is not excessively complex, or if a dynamic range of a few hundred to one is sufficient. At the same time, for large fields of view and complex targets, its variable configuration and capability to use the rotation of the Earth to obtain more complete u-v plane coverage is vital. The size of the array, 20 km per arm of 35 km equivalent overall size, was set by the original operating requirement that it should equal conventional optical telescope resolution (1" at 20 cm, 0.3" at 6 cm). The same considerations will apply to an equivalent optical instrument. The discussion in the beginning of this paper, illustrated by figure 1, indicates that a mapping capability of 10 μarcsec would give a rich scientific return. At this angular scale, significant changes can be expected for both stars and active extragalactic objects within brief timespans. The system must therefore have a large number of elements, as in the case of the VLA, which gives two further advantages: a large number of objects can be studied in a short time because of the "snapshot" capability, and the more complete u-v plane coverage can yield maps of high dynamic range. If the optical array contains 27 elements, each element would have to have a diameter of at least 1 m to give a total collecting area comparable to the Palomar 5-m telescope. The instrument should cover the wavelength range 121.6 nm (Lyman-alpha) to 5 μm; thus, for the mean wavelength of 500 nm, an optical aperture-synthesis array should have a diameter of about 10 km.

One of the major considerations of any concept has to be the phase stability of the system. Incoherent and semicoherent interferometers (the Brown-Twiss interferometer is a brilliant example) have the disadvantages of low signal-to-noise ratio and loss of phase information and so must be rejected. For the complex objects of greatest interest, phase information is essential. This requirement exacts a price; control (or measurement) of the optical paths to $\lambda/20$ means that 25-nm precision is needed at $\lambda = 500$ nm, and proportionally tighter specifications are required as one goes to shorter wavelengths. The radio astronomers, in developing very-long-baseline interferometry (VLBI), have formulated a powerful algorithm for phase and amplitude closure that eases the problem if there are enough receiving apertures. The technique has been applied to VLBI mapping problems with great success (ref. 6). If one has three elements, and hence three baselines, the instrumental phase shifts to total zero. Similarly, if there are four elements in any array, the instrumental perturbations to the amplitudes cancel. As the number of elements increases, the quality of information recovered increases. For N antennas, a fraction $(N - 2)/N$ of the phase information and $(N - 3)/N - 1$ of the amplitude information can be recovered. If N is 10 or more, the procedure appears to be thoroughly reliable. Because the phases must remain stable over the integration period, the precision requirement on the optical paths must be held, but the time for which it is held is reduced. The desired sensitivity and the total collecting area therefore set the final stability specifications.

Two general classes of optical space interferometers have been proposed: stationkeeping, independently orbiting interferometers and structurally mounted arrays. Examples of the first class are SAMSI (ref. 7), in which pairs of telescopes are placed in near-Earth orbit, and TRIO (ref. 8), in which a set of telescopes is maneuvered about the fifth Lagrangian point (L5) in the Earth-Moon system. Among the structural arrays that have been proposed are COSMIC (ref. 9), OASIS, a concept proposed by Noordam, Atherton, and Greenaway (unpublished data), and a variety of follow-on concepts to the Hubble Space Telescope being examined by Bunner (unpublished data). All of these concepts hold promise for giving useful results in the milliarcsecond class, but when the number of elements grows to the order of 27 (or more) and when the spacings extend to 10 km (or even 100 km for 1-µarcsec resolution at $\lambda = 500$ nm), the solutions may prove to be expensive, perhaps prohibitively so.

A third class of optical array becomes feasible, however, if there is a permanently occupied lunar base. The Moon is a most attractive possible location for an optical equivalent of the VLA, capable of microarcsecond resolution.

A Lunar VLA

Assuming that a lunar base has been established, the general outlines of a large optical array following the pattern of the VLA can be visualized with some confidence. A schematic form is shown in figure 3; a set of telescopes, suitably shielded, is deployed at fixed stations along a Y, each arm being 6 km long, for a maximum baseline length of 10 km. There is a fixed station that monitors the telescope location by means of laser interferometers. The telescopes must be movable, but whether they are self-propelled (as shown in fig. 3) or are moved by special transporters (as in the case of the VLA) is a technical detail. The received light signals also are transmitted to the central correlation station, but time delays (not shown in fig. 3) must be inserted to equalize the geometrical time delays (Δt_g) illustrated in figure 2. A number of configurations are possible, probably in the form of laser-monitored moving mirrors.

The individual telescopes might well be approximately 1 m in diameter. The telescopes could be transported in disassembled form; hence, they need not be extremely expensive since launch stress would not be a problem. A simple conceptual design indicates that each telescope might have a mass of 250 kg or less. Then, the total telescope mass for 27 telescopes plus a spare would be about 7 tonnes. The packing volume could be relatively small, since the parts would nest efficiently. The sketch in figure 3 shows each telescope being self-propelled, but if mass transportation to the Moon is a key consideration, one or two special-purpose transporters seem much more likely. Each might have a mass of about 200 kg.

The shielding of the telescopes is an interesting design problem. The simplest scheme would be to adopt the systems used on past space telescopes such as the International Ultraviolet Explorer (IUE), but the construction possibilities on the lunar surface may allow concepts that give dramatic improvements. Instead of being mounted on the telescopes, the shields could be constructed as independent structures that sit on the lunar surface, free of the telescope. The shields might be very simple, low-tolerance, foil and foam baffles, keeping the telescope forever in the shade, radiatively cooled to a very low temperature, or perhaps kept at the average 200-K temperature of the lunar subsurface. It would appear that the thermal stresses might be kept very low by adapting the design to the lunar surface conditions.

Transmission of the received light from the telescopes to the central correlation station must proceed through a set of variable time delays as indicated earlier, and here there is a need for technical studies. For the 10-km maximum baselines proposed here, the maximum time delay rate would be 2.6 cm/sec, which is not excessively high. The requirement of $\lambda/20$ phase stability is challenging; the motion should not have an instability much greater than 10 nm/sec rms, so a smoothness of something better than a part per million is needed. This is not an easy goal, but it is not beyond reason. The curvature of the lunar surface has to be considered unless a convenient crater having a suitably shaped floor can be found. The height of the lunar bulge along a 6-km chord is 2.6 m and, hence, is not a serious obstacle. For the larger concept (60-km baseline, microarcsecond resolution at $\lambda = 500$ nm), the intervening rise of 260 m would be more serious, and suitable refraction wedges or equivalent devices would have to be arrayed along the optical path. The transmitted signal probably should be a quasi-plane wave; this form translates to the requirement that the receiving aperture at the central correlator station still should be in the near field of the transmitting aperture of the most distant telescope. Therefore, the diameter of the transmitted beam must be greater than 10 cm at $\lambda = 500$ nm, and 30 cm for a wavelength of 5 μm. If there were a desire to perform aperture synthesis at $\lambda = 50$ μm (which there might well be), the transmitted beam would have to be at least 1 m in diameter, a requirement that would still be easy to meet since the tolerances would be relaxed.

The characteristics of the central correlator will depend on the results of detailed studies. Two general classes of optical systems can be projected: the "image plane" correlation geometry developed by Labeyrie et al. (ref. 8) for TRIO (a continuation of the traditional technique of Michelson), and the "pupil plane" correlation scheme generally used by radio astronomers, but realized in the optical regime by the astrometric interferometer of Shao et al. (ref. 10).

One interesting advantage generally characteristic of optical interferometry as compared to radio interferometry is the ease with which multibanding circumvents the "delay beam" problem described earlier. Labeyrie (ref. 11) has devised an ingenious dispersive system that efficiently eliminates the problem for most cases. The fringes are displayed in delay space and frequency space, but modern two-dimensional detectors such as charge-coupled devices (CCD's) handle the increased data rate easily.

The data rates are not excessive, being completely comparable to the data rates now handled by the VLA. The 351 cross correlations needed for a 27-element system (or 1404 if all Stokes parameters are derived) requires an average data rate of about 100 kilobauds for a 10-sec integration period; future systems always require larger data rates, but even a projection of an order-of-magnitude increase does not seem to present formidable data transmission problems.

Finally, a word is in order concerning the use of heterodyne systems to convert the optical signals to lower frequencies. The technique is in general use in the radio spectrum, extending to wavelengths as short as 1 mm. Unfortunately, the laws of physics offer no hope for astronomical use of heterodyne techniques at optical and ultraviolet frequencies. Every amplifier produces quantum noise, and the laws of quantum mechanics are inexorable; approximately one spurious photon per second per hertz of bandwidth is produced by every amplifier. At radiofrequencies, the quantum noise is swamped by the incoming signals since there is so little energy per quantum. Optical systems, with bandwidths of 10^{13} or 10^{14} Hz, can afford no such luxury. The crossover in technology occurs at radiation frequency between 100v and 10v. As infrared detectors improve, the shortest wavelength at which heterodyne detectors are practicable will be perhaps 50 µm.

Except for these quantum limitations, the concepts developed for radio techniques carry over to the optical domain. The signal-to-noise analysis differs somewhat. The noise limits are determined by the Rayleigh noise of the system in the radio case, whereas the quantum shot noise of the signal determines the signal-to-noise ratio in an optical system. Otherwise, the extensive software armory developed for radio synthesis systems should be directly applicable to optical interferometers.

Are There Serious Obstacles?

Relatively little thought appears to have been given thus far to the advantages of the Moon as a base for astronomical instruments. There are a number of current misconceptions that seem to hold little substance.

1. Does lunar gravity cause problems? On the whole, the effects of lunar gravity appear to be beneficial. The relatively small (1/6g) acceleration helps to seat bearings and locate contact points, and it generally should provide a reference vector for mechanical systems. The lunar gravity keeps dust settled and thus keeps the density of light-scattering particles low.

Gravitational deflection for telescopes in the 1-m size range is completely negligible. Gravitational deflection does not depend on the weight of a structure; elementary physics shows that the structural deflection s of a structure depends on the length l of the beam, on Young's modulus Y, on the density ρ, on the gravitational acceleration g_m, and on a dimensionless geometrical factor γ that decreases as the depth of the beam increases.

$$s \approx \gamma \left(\frac{\rho}{Y}\right) g_m l^2 \qquad (1)$$

On Earth, 4- and 5-m telescopes have been built with mirror support systems that limit mirror deflection to a fraction of a wavelength of light under full gravity. A 1-m mirror, located on the Moon but otherwise similar, would be stiffer than a terrestrial 4-m mirror by a factor of about 100!

Deflection of the telescope structure can be controlled to high tolerances. Not only are superior materials like carbon-epoxy now available, but improved design methods exist such as the concept of homologous design (introduced by von Hoerner in 1978), in which a structure always deforms to a similar shape. In summary, gravitational deflection poses no problem.

2. What about the thermal environment? The Moon is an approximately 200-K blackbody subtending 2π sr on the underside of a lunar-based instrument. For a conventional satellite in low Earth orbit (LEO), the Earth is an approximately 300-K blackbody subtending nearly 2π sr beneath the spacecraft; however, if the spacecraft is tracking a celestial object, the aspect is changing rapidly – on the order of 4 deg/min. The telescope tracking a celestial source in the lunar environment is changing its aspect at about 0.01 deg/min. When one considers the additional advantage of the natural lunar terrain for better thermal shielding initially and the ability to upgrade its quality at a permanent base, the lunar environment is almost certainly more favorable than LEO from the point of view of thermal stresses. The L5 case is different, since the elements would always be exposed to direct solar radiation.

3. Is scattered light a problem? Again, equipment in LEO has the Earth subtending nearly a hemisphere, but the Earth has high albedo and the Moon has low albedo. The lunar environment is strongly favored, and, as in the thermal case, superior light shielding on the Moon should be achievable.

4. Is direct sunlight a problem? The Sun shines only half the time, and its direction changes slowly. Given the superior light baffling of the lunar-based telescopes, the lunar environment probably will be far superior to either LEO or L5, but thermal studies of real designs should be made.

5. What about lunar dust? The lunar laser retroreflectors have been in service for more than a decade with little performance degradation reported. Dust seems to be no problem, probably because the Moon's gravity settles it rapidly. A very rare meteorite impact nearby might take one or two telescopes out of service, and the choice would have to be made to clean or to replace the instruments.

6. Is seismic activity a problem? The Moon is far quieter than the Earth, with a low background noise. At good seismic stations on the Earth, the seismic noise is less than 0.1 nm rms; the poor locations have high noise because of the effects of wind and surf. Lunar seismic activity is not a concern.

7. Do the solid-body tides of the Moon move the baselines excessively? Earth tides are routinely accommodated by geodesy groups conducting VLBI studies on Earth, where the motions amount to several wavelengths every 12 hours. Although lunar tides are larger in amplitude, they proceed slowly enough that they can be compensated for. The 10-km maximum baseline of a lunar VLA is a smaller fraction of the lunar diameter than the 10 000-km VLB baselines are of the Earth's diameter; therefore, the amplitude of baseline motion is diminished. The net tidal motion of the maximum baseline vector should be on the order of a few tenths of a millimeter. This motion is not negligible, measured in wavelengths of light, but the slow lunar rotation leads to a manageable correction rate on the order of a few wavelengths per hour. The usual interferometric calibration routines should keep this error source under control.

8. Can the baseline reference system be well defined? The analogy with terrestrial VLBI is sufficiently close that the answer has to be affirmative. The errors can be controlled; the lunar soil is sufficiently competent to stably bear the load of a telescope; and, if necessary, hard points can be established to check on vertical motions. Interferometers are largely self-calibrating; there are enough quasi-stable reference points in the sky to enable control of instrumental constants by means of celestial observations.

Summary

A permanent lunar base can provide support for a variety of astronomical investigations. An optical interferometric array, perhaps of the general form of the VLA but designed for optical instead of radio wavelengths, would lead to a qualitative advance in our understanding of the universe. The Y configuration is well suited to expansion, and the capability of the VLA to make maps both rapidly (in its snapshot mode) and with high dynamic range (when multiple array configurations are used) has been demonstrated. Other configurations, such as maximum-entropy-derived circles, certainly should be examined.

A wide variety of scientific problems could be addressed by such an instrument. The stellar analogs of the solar cycle, the behavior of sunspots on other stars, the magnetic field configurations of other stars, and the behavior of dynamic plasma phenomena such as flares and winds are examples of star-related problems that ultimately would lead to both increased understanding of our own Sun and fundamental knowledge of the manner in which stars form and evolve. A wide variety of extragalactic problems could be studied, including the fundamental processes associated with black holes and massive condensed objects as they are manifest in quasars, galactic nuclei, and other optically violent variables. A number of dramatic surprises, in both stellar and extragalactic studies, could be expected, and the instrument certainly would be at the forefront of astronomy from the time of its first use.

No fundamental problems in building such an instrument are apparent. The total mass to be delivered to the lunar surface for the instrument would be 10 to 30 tonnes, which is roughly equivalent to one space station habitat module. The detailed system studies have not been made, but even a preliminary conceptual investigation indicates that the elements of the system are relatively straightforward. The presence of man is highly desirable for this particular instrument; this fact is in marked contrast to the free-flyer case in which the instruments are easily perturbed by human presence.

How long would it take to build the instrument? The answer depends on the time scale of development for a lunar base. Once a clear consensus exists to establish a base on the Moon, development of the components of a lunar VLA could be started and would be ready to be among the first large shipments of non-life-support systems to the Moon. Assembly and development time at the lunar base would depend on the details of the design and on the philosophy of lunar base operations.

Finally, it is clear that a large astronomical community would use the instrument. All the major astronomical facilities on Earth are heavily subscribed, and the VLA probably supports more users than any other astronomical instrument today. An interferometric array has many possible modes of operation: it can take brief snapshots, it can be broken into subarrays to serve multiple-user groups simultaneously for specialized projects, and it can interweave long observing sequences with short projects in an efficient fashion. The VLA supports the observing programs of more than 1000 scientists per year, and a lunar-based optical equivalent could be expected to do the same.

References

1. Dupree, A. K.; Baliunas, S. L.; and Guinan, E. F.: Stars, Atmospheres, and Shells: Potential for High Resolution Imaging. Bull. Am. Astron. Soc., vol. 16, 1984, p. 797.

2. Michelson, A. A.: An Interferometer for Measuring Stellar Diameter. Astrophys. J., vol. 51, 1920, p. 257.

3. Ryle, M.; and Hewish, A.: The Synthesis of a Large Radio Telescope. Mon. Not. R. Astron. Soc., vol. 120, 1960, pp. 220-230.

4. Rogers, A. E. E.: The Two-Element Interferometer. Methods of Experimental Physics, Vol. 12C: Astrophysics, Radio Observations, M. L. Meed, ed., 1976, p. 139.

5. Napier, P. J.; Thompson, A. R.; and Ekers, R. D.: The VLA: A Large Aperture Synthesis Interferometer. IEEE Proc., vol. 71, 1983, p. 1295.

6. Readhead, A. C. S.; and Wilkinson, P. N.: Phase Closure in VLBI. Astrophys. J., vol. 223, 1978, p. 25.

7. Stachnik, R. V.; Ashlin, K.; and Hamilton, S.: Space Station SAMSI: A Spacecraft Array for Michelson Spatial Interferometry. Bull. Am. Astron. Soc., vol. 16, 1984, p. 818.

8. Labeyrie, A.; Authier, B.; Boit, J. L.; DeGraauw, T.; Kibblewhite, E.; Koechlin, L.; Rabout, P.; and Weigelt, G.: TRIO: A Kilometric Optical Array Controlled by Solar Sails. Bull. Am. Astron. Soc., vol. 16, 1984, p. 828.

9. Traub, W. A.; and Carleton, N. P.: COSMIC: A High-Resolution Large Collecting Area Telescope. Bull. Am. Astron. Soc., vol. 16, 1984, p. 810.

10. Shao, M.; Colavita, M.; Staelin, D.; and Johnston, K.: The Technology Requirements for a Small Space-Based Astrometric Interferometer. Bull. Am. Astron. Soc., vol. 16, 1984, p. 750.

11. Labeyrie, A.: Interferometry With Arrays of Large-Aperture Ground-Based Telescopes. Proc. Optical and Infrared Telescopes for the 1990's, A. Hewitt, ed., Kitt Peak National Observatory, Tucson, Ariz., 1980, p. 786.

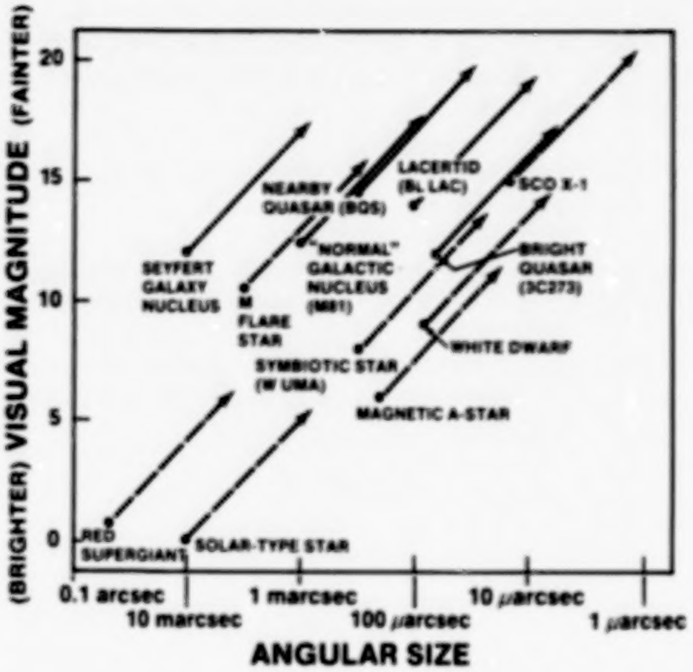

Figure 1.- Visual magnitude as a function of angular size for a selection of stellar and extragalactic objects. The scales are chosen to reflect the largest expected value for each class of object. The length of each upward-sloping line corresponds to a factor of 10 in distance; thus, an object at the tip of an arrow would be 10 times more distant than the closest member of that class designated at the foot of the line.

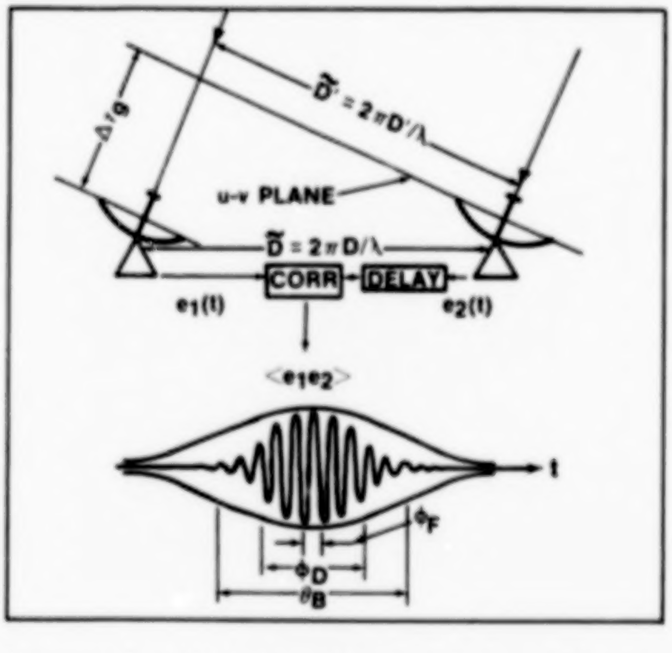
$\Delta\tau_g$
$\tilde{D}' = 2\pi D'/\lambda$
u-v PLANE
$\tilde{D} = 2\pi D/\lambda$
CORR
DELAY
$e_1(t)$
$e_2(t)$
$\langle e_1 e_2 \rangle$
t
ϕ_F
ϕ_D
θ_B

Figure 2.- Schematic diagram of the Michelson stellar interferometer in radio telescope form. The correlator (CORR) output, shown for fixed apertures as a function of time with the direct-current term removed, is equivalent to variation with angle off axis.

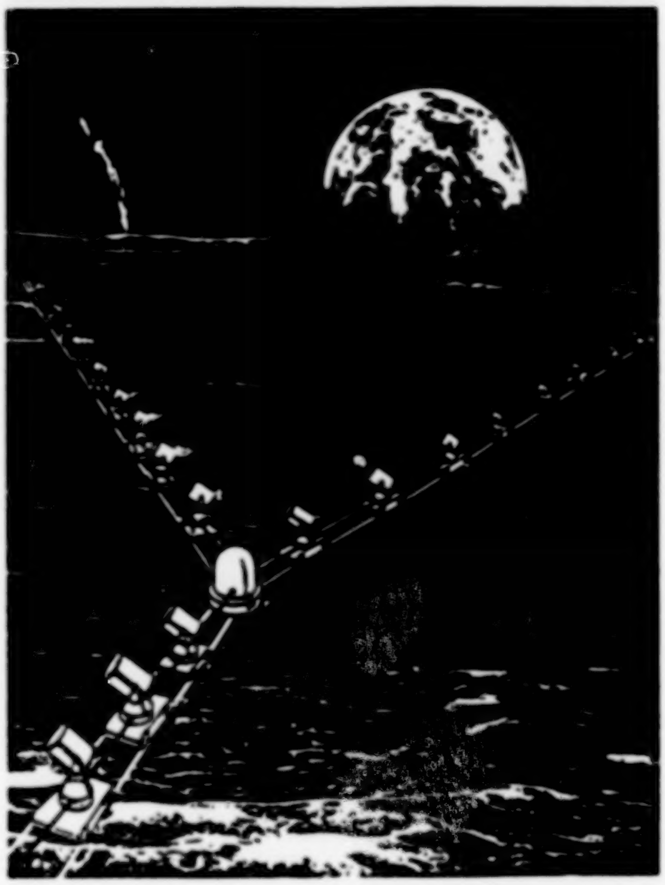

Figure 3.- Schematic view of an optical aperture-synthesis array on the Moon. The individual elements could assume forms very different from the versions shown.

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N89 - 15820

INFRARED ASTRONOMY FROM THE MOON

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The Moon offers some remarkable opportunities for performing infrared astronomy. Although the transportation overhead can be expected to be very large compared with that for facilities in Earth orbit, certain aspects of the lunar environment should allow significant simplifications in the design of telescopes with background-limited performance, at least in some parts of the thermal-infrared spectrum.

Why Leave the Earth To Perform Infrared Astronomy?

Infrared astronomy from ground-based telescopes is severely handicapped compared to that possible with observations from outside the atmosphere. A serious problem caused by the atmosphere is absorption (and reemission) of light in large swaths across the infrared spectrum. At wavelengths between 1 and 20 μm, less than half the spectrum of an astronomical source can be seen from the ground. At longer wavelengths out to roughly 1 mm, almost none of the light gets through to the telescope. Much of this absorption is due to water vapor, which can be substantially avoided by stratospheric telescope platforms, but large pieces of the spectrum remain obscured by species with longer scale height, such as carbon dioxide and ozone. Even at wavelengths at which the atmosphere is fairly transparent, thermal emission from a warm telescope and the atmosphere constitutes the ultimate limitation on infrared sensitivity to faint sources.

Although the effects of "seeing" are somewhat smaller at infrared than at optical wavelengths (i.e., the seeing disk is about half the size at 10 μm compared to that in the visible), most infrared imaging that is possible from the ground has been done in seeing-limited pixels. Observations from outside the atmosphere render the point source profile (PSP) completely diffraction-limited, and thus highly stable. Such PSP stability will allow us to take maximum advantage of superresolution techniques that allow the Rayleigh limit to be exceeded.

Why Go All the Way to the Moon?

The lunar environment offers certain advantages over Earth orbit for performing infrared astronomy. The modest lunar gravity, although perhaps an operational disadvantage in the construction of a large facility, yields the convenience of superb pointing stability. Lunar telescopes will not be subjected to the varying gravitational torques and residual atmospheric drag associated with Earth-orbiting telescopes. The lunar surface also provides exceptionally stable baselines for coherent infrared interferometry.

The vacuum on the Moon is superb ($\sim 10^{-12}$ torr), even by comparison to Earth orbit. Low Earth orbit (LEO) telescopes are expected to see strong emission lines as a result of excitation of residual atmospheric molecules by collision with the spacecraft. Special care must be taken with cryogenic LEO telescopes to avoid icing the optics with these residual gases. Neither of these effects is expected to be important on the Moon.

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The combination of excellent lunar vacuum and the massive thermal shielding, provided, for example, by the walls of a crater near a lunar pole, provides an opportunity for efficient passive cooling of a lunar telescope. This is a great advantage in that cryogen consumption may be minimized or even avoided entirely. For a well-designed telescope, one that is radiatively decoupled from the lunar soil, is shielded from direct or diffracted sunlight, has a structure that is blackened to ensure excellent thermal coupling to the cold sky, and is isolated from dissipative electronics, the entire structure will efficiently cool as it passively radiates to space. How cold can a passively cooled lunar telescope get? Lunar soil cools to ~90 K by the end of the lunar night, and small, specialized Earth-orbit packages (the exteriors of which are bathed, throughout their orbits, by sunlight and earthlight) have been sustained passively to temperatures as low as ~100 K. Therefore, one can expect even better performance from a well-designed, optimally situated lunar telescope. Figure 1 is a comparison of the celestial background power with that from a telescope of different temperatures and illustrates the advantage of cooled optics. The solid lines indicate the celestial background, whereas the dashed lines indicate the background from a clean telescope. It should be noted that the background emission from a 300-K ground-based telescope is orders of magnitude higher than anything shown in this figure. We can see from this figure that, for example, if it is possible to passively cool a lunar telescope to ~60 K or less, celestial background-limited data can be obtained to a wavelength of about 200 μm.

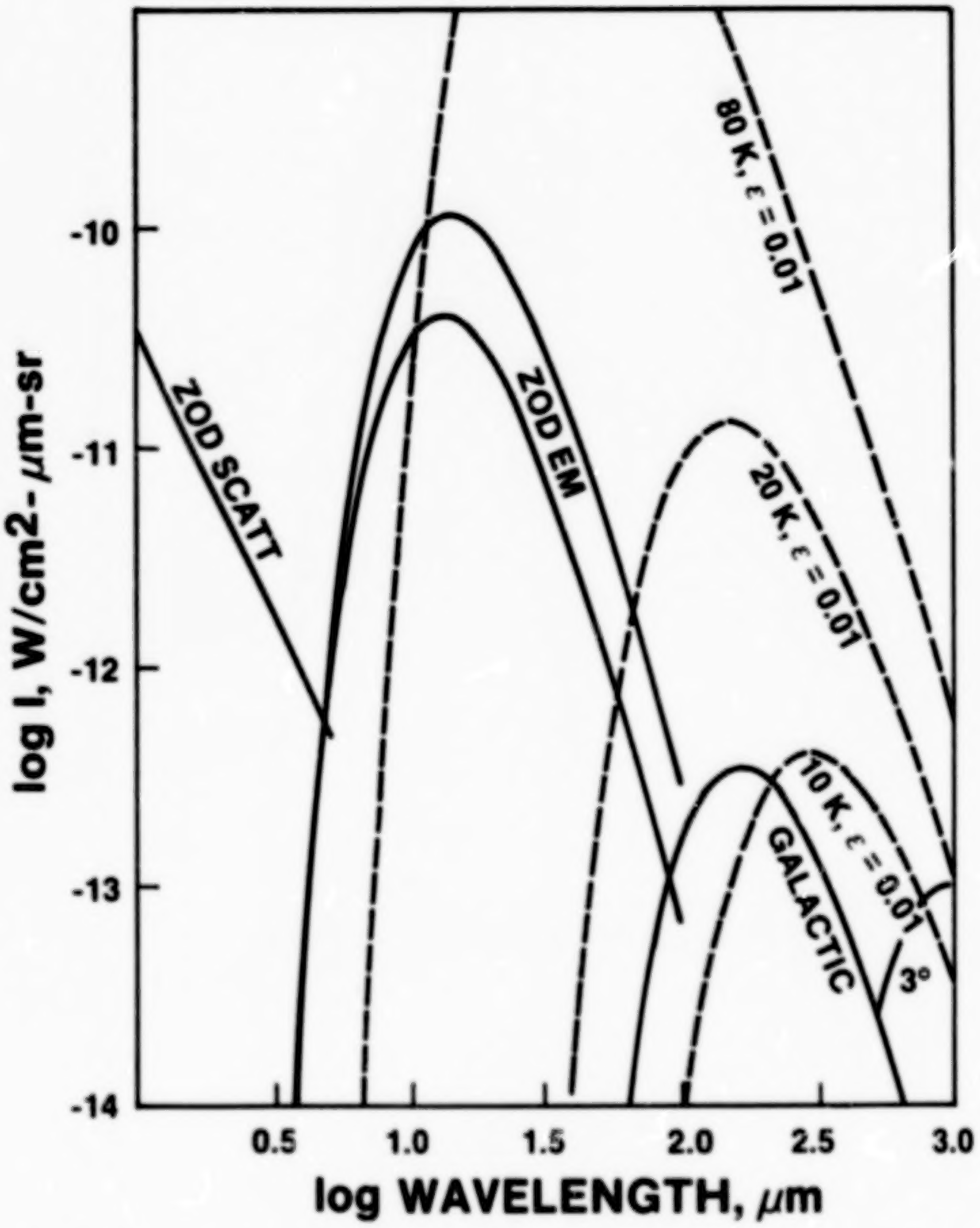

Figure 1. - Comparison of celestial background power (solid lines) with background power from a clean telescope of different temperatures (dashed lines).

PART III
LUNAR RADIOFREQUENCY TELESCOPES

The response of those who attended the workshop and the number of papers that were written on radio astronomy indicate that participants are enthusiastic about the possibilities afforded radio astronomy by the establishment of a lunar base. Some interesting new applications of current ground-based radio telescopes and the opening of the last window in the electromagnetic spectrum at very low frequencies make radio astronomy observatories on the Moon a particularly attractive idea.

In the first paper, F. D. Drake proposes the use of the natural bowl shape of craters on the Moon to construct large, single-dish antennas similar to the design of the Arecibo telescope in Puerto Rico. In the second paper, R. Linfield describes the manner in which a lunar version of the very large array (VLA) radio telescope would vastly improve our ability to perform astrometry, with accuracies increasing by two orders of magnitude over the VLA in New Mexico. The primary advantage of having a lunar VLA radio telescope stems from the absence of a lunar troposphere. The increase in radio interferometry baselines to ultralong dimensions between the Moon and the Earth is discussed in the next two papers by J. O. Burns and by B. Dennison. Burns describes an extension of the very-long-baseline technique currently used with ground-based telescopes which will produce a resolution of 0.4 μarcsec at 300 GHz. Dennison notes that at frequencies less than approximately 5 GHz, such an ultra-long-baseline interferometer will be limited by scattering from the interstellar medium. In the fifth paper, J. Douglas and H. Smith discuss opening the low-frequency window to astronomy by placing a telescope on the lunar far side. The natural insulation of the Moon will filter out the manmade interference from the Earth at a frequency of a few megahertz. The lunar far side is virtually the only location in the inner solar system for a practical very low frequency array. In the final paper in part III, B. M. Oliver explores the possibilities of using lunar-based radio antennas in search of intelligent extraterrestrial communications.

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N89 - 15821

VERY LARGE ARECIBO-TYPE TELESCOPES

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Abstract

The Arecibo-type radio telescope, based on a fixed spherical reflector, is a very effective design for a large radio telescope on the Moon. In such telescopes, major structural "members" are provided by the ground on which they are built, and thus are provided at no cost in materials or transportation. The bulk of the remaining structure is made up of members which are always in tension and thus can be very simple; indeed, most of the structure can be made from cables.

The strong compression members, the tall towers which support the suspended platform, are an expensive part of the actual Arecibo telescope. The need for such towers can be eliminated if a suitable valley or crater can be found wherein the rim of the depression can be used as the support point for the cables which support the suspended platform. Reasonable valley and crater cross sections fulfill this need quite nicely. In this case, a substantial saving in cost and materials accrues. This approach could be used to build Arecibo-style telescopes on the Moon or on the Earth at substantial savings over the cost of the actual Arecibo design. See figure 1.

With an Arecibo-type radio telescope on the Moon, there are no changing gravity loads because of the design and no changing wind loads because of the location; therefore, the only source of time variation in the telescope geometry is thermal changes. The actual Arecibo telescope has built into it simple relationships between structural cross sections which cause critical points, such as the location of the reflector surface or of the suspended platform, to remain fixed in space when the temperature changes. This configuration can be achieved through the use of conventional materials and with no requirement for active controls. These techniques could be used with a lunar telescope to eliminate thermal changes in crucial telescope dimensions.

Calculations show that with conventional materials, such as steel, it should be possible to construct an Arecibo-type telescope with a reflector diameter of some 30 km on the Moon, and with a reflector diameter of some 60 to 90 km if materials of high specific strength are used.

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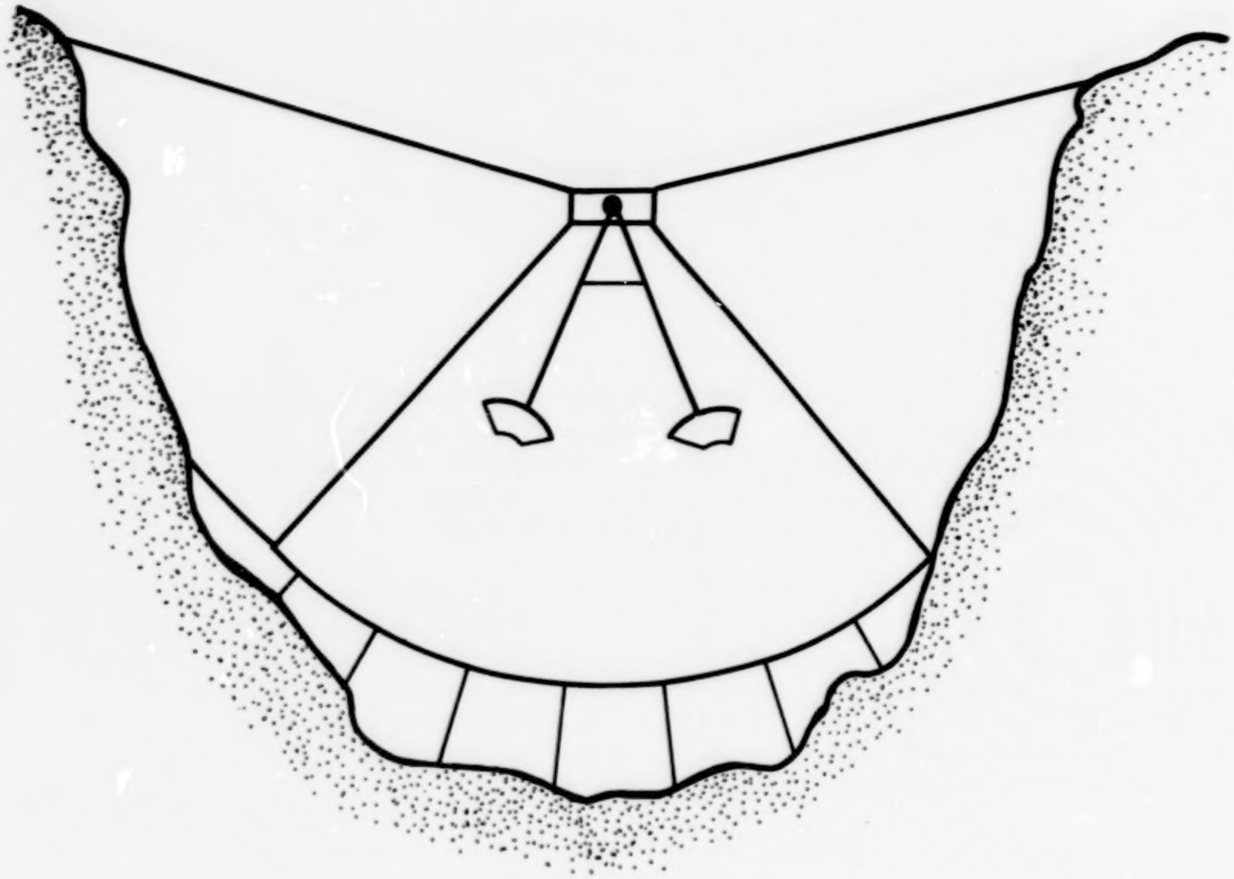

Figure 1.- Proposed emplacement of a very large radio telescope in a crater using a cable suspension system to stabilize the instrumentation platform.

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N89 - 15822

LUNAR RADIO ASTROMETRY

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Abstract

The accuracy of Earth-based radio astrometry is limited in a fundamental way by the variable delay of the troposphere and by the centimeter-scale motions of a dynamic Earth. Going to Earth orbit solves the variable-delay problems, but problems with evolution of the baseline vector remain. The Moon can provide a stable platform where the potential accuracy of radio astrometry is one to two orders of magnitude better than from the Earth.

Background

Radio astrometry can be broadly separated into two types.

1. Connected-element interferometry – With this type of radio astrometry, the local oscillator (LO) signal is distributed and the relative phase at the two ends of a baseline is measured. The angular measurement precision is

$$\Delta\theta \sim \frac{\lambda}{D\,SNR}$$

where λ is the wavelength of observation, D is the baseline, and SNR is the signal-to-noise ratio; $SNR \propto (BW_{tot})^{0.5}$, where BW_{tot} is the total correlated bandwidth.

2. VLBI – In this type of radio astrometry, independent LO's are used and the relative arrival time at the two ends of a baseline is measured by bandwidth synthesis (BWS). The angular measurement precision is

$$\Delta\theta \sim \frac{c}{D\,BW_{span}\,SNR}$$

where c is the speed of light and BW_{span} is the spanned bandwidth, which is generally larger than BW_{tot}. As in the other case, $SNR \propto (BW_{tot})^{0.5}$.

Current Accuracy and Limitations

Currently, on Earth, very-long-baseline interferometry (VLBI) yields higher accuracy astrometry than does connected-element interferometry. The accuracy, as determined by comparing independent VLBI catalogs, is approximately 3 marcsec and is limited primarily by two effects. The first is the delay introduced by the troposphere: typically 7 nsec and highly variable. Much of this variation is due to water vapor and is difficult to calibrate. Water vapor radiometers enable an estimate of the delay by measurement of the brightness temperature of atmospheric water vapor emission at 22 GHz. The accuracy of this method is limited by uncertainty in the (variable) vertical distribution of water vapor in the troposphere; this effect may fundamentally limit the accuracy of Earth-based astrometry at about the 1-marcsec level.

The second major error source involves the evolution of the baseline vector between the two telescopes. This evolution is primarily the result of the (nearly) constant rotation of the Earth, but numerous secondary effects (e.g., polar motion, short-term variations in rotation rate, solid Earth tides, variable atmospheric and ocean loading on the continents) are important for accuracies below about 50 marcsec. Because of the active dynamics of the Earth, it is difficult to calibrate these effects to high precision. Their short time scales (< 1 day) and stochastic nature may also introduce an ultimate limitation of ~1 marcsec to Earth-based astrometric accuracy.

Lunar Radio Astrometry

Use of the Moon as a platform for astrometry offers a chance to completely escape the effects of the troposphere and to greatly reduce the effects of baseline evolution. Consider an instrument of three identical antennas on the Moon arranged in an equilateral triangle. Antenna separations (baselines) would lie somewhere in the 100- to 2000-km range. The lunar environment would allow use of very lightweight (possibly remotely deployed) antennas with diameters of 10 to 15 m. Whether the instrument would give higher accuracy in a connected-element (distributed LO) mode or VLBI (separate LO's) mode is not certain. Over short distances, the LO signal could probably be distributed very accurately by cable or microwave link between relay towers; over longer distances, it might have to travel by satellite, and the path length uncertainty would be a problem. Both operating modes will be considered. For either mode, the received data would be amplified, mixed to a lower frequency, and transmitted to a single site (probably at a human colony) for real-time correlation of ~500-MHz bandwidth. Correlated data plus calibration and bookkeeping information could be transmitted to Earth for analysis. Either a low-bandwidth link or the regular delivery of data on tape would suffice. Power for the antennas could be supplied by solar cells with storage batteries for the lunar night; by this means, the instrument could operate continuously.

Error Analysis of Proposed Instrument

Propagation effects are a major error source on Earth. The Moon has no troposphere, but there will be some delay introduced by charged particles in the lunar ionosphere, in the solar wind, and (occasionally) in the Earth's magnetotail. This effect, already small, can probably be reduced to insignificance by observing at high frequencies (20 to 30 GHz), since the delay varies as the square of the observing wavelength. If necessary, the effect of charged particles can be completely removed with dual-frequency observations, as is often done on Earth with simultaneous 2.2-GHz and 8.4-GHz measurements.

Baseline knowledge is the other limiting error source on Earth. As revealed by lunar laser ranging, the situation on the Moon is quite different. The nonlinear terms in the lunar rotation rate are as large as for the Earth, but they are much more predictable. The Moon has no fluid sheath around it and is much quieter dynamically than is the Earth. At the level of 0.1 marcsec, there are about 30 constant terms in the lunar potential and elasticity (e.g., Love numbers for solid-body tides) which would need to be measured to adequately describe the baseline evolution. These quantities would be solved for as part of a global fit to the delay or phase measurements made with the interferometer. The stochastic component of the Moon's motion is about 100 times smaller than that of the Earth, and it varies much more slowly (time scales of 1 month and longer). Therefore, it can

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easily be solved for from the data. Lunar motions should have no effect on accuracy at the 0.1-marcsec level if appropriate care is taken.

Source structure will cause systematic errors in astrometric measurements. This effect is most serious for bandwidth-synthesis measurements of a source which is significantly resolved, and can be many milliarcseconds in size. The baselines of the proposed lunar interferometer are sufficiently short that there will be many nearly unresolved sources (especially at 20 to 30 GHz); the interferometer could concentrate exclusively on such objects. In that case, the measured astrometric position will be the emission centroid at that frequency.

High observing frequencies (20 GHz or higher) are thus desirable, as source sizes shrink with increasing frequency for most sources, and the centroid should be closer to the massive "central engine" powering the source than at lower frequencies. At 30 GHz, many sources will be 0.1 to 1.0 marcsec in extent. Time variation of the emission centroid is of concern, particularly for superluminal sources of moderate size such as 3C 345 and 3C 273. The VLBI maps made on Earth will be of help in this instance and should be useful in calibrating this time variation to 0.1 marcsec or better. Many sources will have structure much less variable than that of 3C 345, and this calibration will not be necessary.

Signal to noise will be more of a limitation than for Earth-based astrometry. When compared to antennas and receivers used on Earth, the lunar antennas will be smaller, and, because of the expense of refrigeration, the receivers may be of lesser quality. Furthermore, the baselines are shorter, and the required accuracy is higher. A 1-year observing program on 500 sources will allow 100 10-minute scans per source. The sensitivity limitations on angular accuracy are as follows.

1. For BWS (VLBI),

$$\Delta\theta = \frac{0.06 \text{ marcsec } T_{50}}{D_{1000} S_{0.2} (BW_{500})^{0.5} d_{15}^2 BW_{span}}$$

2. For radiofrequency (RF) phase measurement (connected-element interferometry),

$$\Delta\theta = \frac{0.006 \text{ marcsec } T_{50}}{D_{100} S_{0.2} (BW_{500})^{0.5} d_{15}^2 \nu_{30}}$$

Here, T_{50} is the system temperature in units of 50 K, D is the antenna separation (in units of 1000 km for VLBI, 100 km for connected-element interferometry), $S_{0.2}$ is the correlated flux in units of 0.2 Jy, BW_{500} is the correlated bandwidth in units of 500 MHz, d_{15} is the antenna diameter in units of 15 m, BW_{span} is the spanned bandwidth in units of 1 GHz, and ν_{30} is the observing frequency in units of 30 GHz.

Instrumental effects will be a major problem. For VLBI observations, the quality of the local oscillators will probably be the critical issue. Hydrogen masers have errors of ~40 psec in 10^4 sec, but 0.1 marcsec corresponds to a delay precision of 1.5 psec over a 1000-km baseline. A new generation of frequency standards would be required.

For connected-element observations, the clock quality is not critical. However, as 0.1 marcsec corresponds to a delay of only 0.15 psec (0.05 mm light travel time) over a 100-km baseline, extreme care would be needed in the distribution of the local oscillator signal and in the calibration of any instrumental phase and delay effects. This constraint would probably pose the greatest technical difficulty to performance of astrometry with an accuracy of 0.1 marcsec or better. Three possible ways to improve the accuracy are

1. Increase baseline length to decrease the sensitivity to the effect.

2. Use round-trip transmission to cancel out length variations in the LO signal transmission path.

3. Distribute the LO signal from a satellite in Earth geosynchronous orbit. Any errors in knowledge of the satellite orbit would be reduced by the ratio of baseline length to Earth-Moon separation.

Applications of Sub-0.1-Milliarcsecond Astrometry

An improvement in astrometric accuracy by more than an order of magnitude would have significant astronomical implications. A search for quasar proper motions would be of interest. The absolute motions of components in superluminal sources could be measured. On a galactic scale, it would be possible to measure the Sun's motion about the galactic center (5 marcsec/yr, allowing a 2% measurement in just 1 year). By observing a number of water masers (not possible with BWS) and radio stars, definitive studies of galactic dynamics become possible.

Spacecraft navigation would be helped by such high-precision astrometry. Missions to the outer solar system and beyond would benefit especially. An error of 0.1 marcsec corresponds to 2 km at Neptune's orbit and 15 000 km (0.0001 AU) at 1 pc.

N89-15823

MERI: AN ULTRA-LONG-BASELINE MOON-EARTH RADIO INTERFEROMETER

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Introduction

Radiofrequency aperture synthesis, pioneered by Ryle and his colleagues at Cambridge in the 1960's, has evolved to ever longer baselines and larger arrays in recent years. The European Very Long Baseline Network and the National Radio Astronomy Observatory's Very Long Baseline Array, currently under construction, use a large fraction of the Earth's diameter to synthesize apertures with resolutions of milliarcseconds at centimeter wavelengths. These arrays sample the Fourier components of a distant radio source's brightness distribution using the Earth's rotation to increase the coverage in the Fourier domain. Maps of the radio surface brightness are produced by performing Fourier transforms on the source visibilities gathered from the correlated signals of the radio antenna pairs. Tropospheric, ionospheric, and system-related contamination of the source visibilities can be removed by iterative modeling, termed hybrid mapping or self-calibration (ref. 1). A variety of deconvolution algorithms such as CLEAN and Maximum Entropy can remove the diffraction effects in maps produced by incomplete sampling of the Fourier transform plane (i.e., incomplete aperture). This process results in maps of increasing quality with milliarcsecond resolution and dynamic ranges of hundreds to one.

The limiting resolution at a given frequency for modern ground-based very-long-baseline (VLB) interferometry (VLBI) is simply determined by the physical diameter of the Earth. There are no other technological barriers that constrain VLB observations at centimeter wavelengths. This limitation can, of course, be overcome by placing radio antennas in orbit around the Earth. A first step toward space-based VLBI may occur within the next decade. A joint mission proposed to the European Space Agency (ESA) and to NASA would place a free-flying 15-m radiofrequency antenna in elliptical orbit about the Earth (ref. 2). This project, termed Quasat for quasar satellite, would have an orbital perigee of about 4000 km and an apogee of about 15 500 km and would be inclined by 63° to the Earth's Equator. The operating frequencies would be between 22 and 1.7 GHz. The resolution would increase that of the ground-based VLBI by a factor of 3 or 4. The superior sampling of spatial frequencies (projected baselines) would also greatly enhance the quality of maps by reducing the ambiguities usually encountered in the image restoration process. The Quasat antenna would be linked to ground-based VLB antennas with telemetry commands (including clock reference) relayed from the ground. During the observations, data would be recorded on magnetic tape. Later, the tapes would be brought to a central processing station for correlation and mapping.

A second-generation, totally space-based VLB network was proposed recently by a group at the Naval Research Laboratory (NRL) (ref. 3). The Astro-Array would consist of 30 spaceborne antennas with no ground-based elements and with the correlator station also in space. Each antenna would be 50 m in diameter and placed in orbits that would yield minimum and maximum baselines of 1000 km and 200 000 km, respectively. The resolution of the Astro-Array at 5 GHz would be <0.1 marcsec. The array receivers would operate in the frequency range of 30 MHz to 300 GHz. Since the entire array would be above the Earth's atmosphere and therefore not subjected to atmospheric wave scattering and uncertainties in baseline positions, it could act as a phased-linked interferometer. Real-time correlations of source visibilities, via satellite links, would remove many of the uncertainties that limit ground-based VLBI. Diffraction-limited resolution at higher frequencies and dynamic ranges of tens of thousands to one (limited only by system clocking and correlator errors) would then be possible.

The next logical extension of space-based VLBI would be a station or stations on the Moon. I originally proposed this concept, termed MERI for Moon-Earth radio interferometer, at the NASA Symposium on Lunar Bases and Space Activities of the 21st Century held in Washington, D.C. (ref. 4). The Moon could serve as an outpost or even the primary correlator station for an extended array of space-based antennas. Because of the stability of the lunar surface, the natural cryogenic environment, and the proximity to scientists on the lunar base, one may wish to build the counterpart of the very long array (VLA) radio interferometer (ref. 5) on the Moon (fig. 1). Such a lunar VLA alone would be capable of impressive new science, especially in astrometry (ref. 6). But, as part of a larger VLBI network, the combined resolution and sensitivity would allow us to probe far deeper into the universe and with much greater spatial resolution than previously possible.

Resolutions, Wavelengths, and Sensitivities

As a guide to the potential radiofrequency science that would be possible with MERI, I propose a two-component array consisting of the Astro-Array and a lunar VLA. Furthermore, I will presume that the system parameters are those given in table I with uniform antenna apertures of 50 m. The baselines for such an array of telescopes would range from a minimum of about 200 m (for the lunar VLA) to an instantaneous maximum of about 500 000 km (about 5 times that of the Astro-Array alone). Over the 2-week, half-sidereal period of the Moon, the maximum baseline could be doubled to 10^6 km.

Such a configuration has four distinct advantages. First, this MERI array would offer an unprecedented resolving power as is discussed further below. Second, the wide range of spatial frequencies that would be sampled by these baselines offers us an opportunity to study an amazingly broad spectrum of structures in radio sources. Third, the sensitivity of the array – far greater than that of any interferometer currently in existence – would enable the resolution and mapping of weak, fine-scale structure. Fourth, the combination of short (hundreds of meters to kilometers) to intermediate (thousands of kilometers) to very long (hundreds of thousands of kilometers) spacings in an airless environment would allow us to reconstruct the radio source brightness distributions with a minimum of uncertainty.

The resolution of MERI would be governed by two factors. At high frequencies, the interferometer is diffraction-limited. The smallest resolvable feature (full width half maximum (FWHM)) is given by

$$\theta_{diff}(\mu\text{arcsec}) = 6.3 \times 10^{7} (\nu_{GHz} D_{km})^{-1} \tag{1}$$

where ν_{GHz} is the frequency in gigahertz and D_{km} is the baseline in kilometers. For an instantaneous baseline of 500 000 km, the resolution at 10 GHz is 12.6 μarcsec and at 300 GHz is 0.4 μarcsec. These resolutions are improved further by a factor of 2 for aperture synthesis using a half revolution of the Moon around the Earth.

At lower frequencies, the resolution of MERI is limited by electron density turbulence as the radiofrequency radiation passes through the interstellar medium (ISM) of the Milky Way. (See ref. 7.) This turbulence causes the radio sources to be broadened angularly in a manner that depends upon the line-of-sight direction to the source. Recent VLB measurements, interplanetary scintillations of extragalactic sources, and interstellar scintillations of pulsars have been used to constrain the amount of broadening by the ISM. Cordes et al. (ref. 8) and Dennison et al. (ref. 7) find that the scattering angle for a plane-wave source is given by

$$\theta_{ISS}(\mu\mathrm{arcsec}) = 1.33 \times 10^{5}(L_{kpc} < C_{n}^{2} >)^{3/5} \nu_{GHz}^{-11/5}$$

$$\approx 10^{3} \nu_{GHz}^{-11/5} (\sin|b|)^{-3/5} \tag{2}$$

assuming a power-law spectrum of turbulence in the form $C_n k^{-3.6}$, where k is the wave number; L_{kpc} is the effective path length in kiloparsec, ν_{GHz} is the frequency of observation in gigahertz, and b is the galactic latitude (where eq. (2) is valid for $b \gtrsim 10°$). Pulsar interstellar scintillation measurements suggest that C_n^2 is about $10^{-3.5}$.

Equating equation (1) to equation (2) yields the frequency above which the MERI observations are diffraction-limited:

$$\nu_{GHz} > 10^{-4} (\sin|b|)^{-1/2} D_{km}^{5/6} \tag{3}$$

For high galactic latitudes and an instantaneous baseline of 500 000 km, this frequency is 5.6 GHz. Above this frequency, the resolution of the MERI array is given by equation (1). Below this frequency, the resolution of the array is limited by turbulence broadening and is given by equation (2).

The sensitivity of the MERI array (ref. 9) is given by

$$S_{rms}(\mathrm{mJy}) = 5.55 \times 10^{3} (\frac{T}{\varepsilon}) D^{-2} (\Delta\nu_{MHz}\, tN(N-1)/2)^{-1/2} \tag{4}$$

where S_{rms} is the rms noise for the system with receiver system temperature T, antenna efficiency ε, antenna diameter D, bandwidth $\Delta\nu_{MHz}$, integration time t, and number of antennas N. To correspond to a one-bit digital correlator of the type currently used for VLB observations, a correlator efficiency of 64% has been assumed. For $T = 50$ K, $\varepsilon = 0.65$, $D = 50$ m, $\Delta\nu = 50$ MHz (at 10 GHz wavelength), $t = 6$ hr × 3600 sec/hr, and $N = 60$, the rms sensitivity is 4 μJy. This is a factor of 10 more sensitive than the VLA, which is currently the most sensitive aperture-synthesis telescope in the world.

The combination of high resolution and sensitivity with MERI will allow radio astronomers to probe a far greater range of source structures at larger distances than ever before. As a result, the science with MERI will be far ranging and should greatly advance radio astrophysics.

Radio Astrophysics With MERI

A wide variety of astronomical observations at radiofrequencies can be undertaken with the MERI array ranging from observations within our solar system of active regions on the Sun and the magnetosphere of Jupiter to examination of the nuclei of active galaxies and quasars. Table II contains the spatial resolutions of a variety of galactic and extragalactic objects that could be observed with MERI at 10-GHz and 300-GHz frequencies.

Many of the important radio observations that could be conducted with MERI involve astrometry. Let me consider a few fundamental astrometry experiments.

1. The potential <0.1-parcsec position accuracy of MERI could be used to improve upon the current celestial coordinate system. In particular, the combination of an optical interferometer on the Moon (refs. 10 and 11) and MERI could be used to refine the relationship between the optical and the radiofrequency coordinate systems.

2. It may be possible to search for dark companion stars (black holes and neutron stars) or even planets around radio stars by measuring the perturbations of radio star proper motions.

3. Relative astrometry can be used to measure the expansion of radio source components in extragalactic jets. Resolutions and sensitivities of current VLB interferometers are generally not high enough to conduct such observations.

4. A particularly exciting prospect involves the fundamental cosmological experiments that could be performed. Morgan (ref. 12) has described the manner in which H_2O masers in our galaxy can be used as independent distance measures through the use of classical statistical parallax techniques. The angular resolution of MERI could enable radio astronomers to extend this technique to other galaxies and to accurately determine their distances. Thus, a powerful new tool is at hand for measuring the Hubble parameter. Similarly, trigonometric parallax measurements of radio galaxies in clusters combined with redshift measurements could allow us to determine distances to clusters and thus to further calibrate the extragalactic distance scale.

There are also various aperture-synthesis observations that one might wish to perform with MERI. Some of these include:

1. Mapping radio burst regions on other stars — Enough sensitivity and resolution exists with MERI to refine our understanding of the solar-stellar connection.

2. High-resolution mapping of radio stars such as SS433 and RS CVn — Some of these stars may serve as scaled-down prototypes of the engines at the cores of active galaxies and quasars.

3. Mapping the core of the Milky Way — Recent radio observations of the Sag A region of our galaxy have revealed a great deal of complex structure, both thermal and nonthermal in origin. The MERI could be used to probe the source of this activity at very high spatial resolution and sensitivity.

4. Studying the collimation of radio jets very close to the core of active galaxies and quasars — The radio jets hold the key to transporting magnetized plasma from the "engines" at the centers of galaxies to the extended lobes or tails. Currently, we cannot determine the manner in which the radio jets are first collimated; therefore, we are missing a key element in understanding the physics of radio jets.

5. Mapping the engines in nearby active galaxies — For the first time, the MERI array provides sufficient resolution and sensitivity to map the accretion disks around the compact object that is fueling the radio emission. We may be able to get a direct answer to the question, "Do giant black holes power active galaxies?"

6. Testing fundamental physics of compact extragalactic sources — Researchers such as Kellermann and Pauliny-Toth (ref. 13) believe that the region which we can resolve near the core of a galaxy will be limited by the so-called Compton catastrophe. The maximum brightness temperature that is visible from such a source is 10^{12} K. Inverse Compton scattering of radio photons by relativistic electrons near the core makes the central region of the source effectively opaque. By observing the source sizes at a variety of wavelengths and resolutions with MERI, we can test this basic physical process.

The MERI array will open an entirely new regime of wavelengths, resolutions, and sensitivities for radio astronomy. As with any such leap in astronomical instrumentation, this advancement will result in the observation of a variety of known radio sources and the exploration of their structures in unprecedented detail. Even so, it may be the serendipitous discoveries, which are by definition impossible to predict, that ultimately justify the construction of MERI.

Acknowledgment

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References

1. Pearson, T. J.; and Readhead, A. C. S.: Annu. Rev. Astron. Astrophys., vol. 22, 1984, p. 97.

2. Burke, W. R., compiler: QUASAT — A VLBI Observatory in Space. ESA Scientific Publications (the Netherlands), 1984.

3. Weiler, K. W.; Spencer, J. H.; and Johnston, K. J.: NRL Memorandum Report 5657, 1985.

4. Burns, J. O.: In Lunar Bases and Space Activities of the 21st Century, W. W. Mendell, ed., Lunar and Planetary Institute (Houston, Tex.), 1985, p. 293.

5. Napier, P. J.; Thompson, A. R.; and Ekers, R. D.: Proc. IEEE, vol. 71, 1983, p. 1295.

6. Linfield, R.: 1986, this workshop.

7. Dennison, B.; Thomas, M.; Booth, R. S.; Brown, R. L.; Broderick, J. J.; and Condon, J. J.: Astron. Astrophys., vol. 135, 1984, p. 199.

8. Cordes, J. M.; Ananthakrishnan, S.; and Dennison, B.: Nature, vol. 309, 1984, p. 689.

9. Christiansen, W. N.; and Hogbom, J. A.: Radiotelescopes. Cambridge University Press (New York), 1985, chapter 8.

10. Burke, B.: In Lunar Bases and Space Activities of the 21st Century, W. W. Mendell, ed., Lunar and Planetary Institute (Houston, Tex.), 1985, p. 281.

11. Burke, B.: 1986, this workshop.

12. Morgan, J. M.: Nature, vol. 310, 1984, p. 270.

13. Kellermann, K. I.; and Pauliny-Toth, I. I. K.: Annu. Rev. Astron. Astrophys., vol. 19, 1981, p. 373.

TABLE I.- CHARACTERISTICS OF THE MERI ARRAY

Number of antennas	[a]60
Antenna size, m	50
Antenna efficiency	0.65
Frequency coverage, MHz	30 to 300 000
Bandwidth, % of frequency	10
System temperature, K	50
Baselines	
Minimum for lunar VLA, m	200
Maximum for instantaneous observations, km	500 000
Maximum for half-sidereal period synthesis, km	10^6
Resolution	
At 100 MHz,[b] arcsec	0.2
At 10 GHz,[c] μarcsec	12.6
At 300 GHz,[c] μarcsec	0.4
Sensitivity in 6 hr, μJy rms	4

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[a] 30 in Earth orbit and 30 on the Moon.
[b] Limited by interstellar turbulence broadening.
[c] Assuming observations near the galactic poles.

TABLE II.- SPATIAL RESOLUTIONS AT 10 AND 300 GHz

Object	Linear resolutions (FWHM), m (AU), at frequency of–		Scientific goals or items of interest
	10 GHz	300 GHz	
Sun	9	3	Solar flare activity
Mercury	5	1.6	Differential heating of surface by solar wind
Jupiter	40	12	Mapping of magnetosphere
Ux Ari	9.7×10^7	3.1×10^7	Solar-stellar connection
Orion nebula	9.7×10^8	3.1×10^8	Starbirth; bipolar outflow
SS433	9.7×10^9	3.1×10^9	Formations of radio jets; mini-engine
Sag A (galactic center)	1.95×10^{10} (0.13)[a]	0.6×10^{10} (0.04)[b]	Engine at galaxy core
M31	109.5×10^{10} (7.3)	34.5×10^{10} (2.3)	Comparison of closest spiral galaxy to Milky Way
Centaurus A	57×10^{11} (38)	18×10^{11} (12)	Engine powering active galaxy; collimation of radio jets
Perseus cluster	136.1×10^{12} (907)	43.5×10^{12} (290)	Trigonometric parallax for radio galaxies
3C273	945×10^{12} (6300)	300×10^{12} (2000)	Radiofrequency activity in quasars

[a] $6.5R_s$; R_s = Schwarzschild radius for $10^6 M_o$ black hole.
[b] $2.1R_s$.

Figure 1.- Retouched photograph showing a very long array of antennas constituting a radiofrequency interferometer emplaced on the Moon.

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N89-15824

RADIOWAVE SCATTERING AND ULTRA-LONG-BASELINE INTERFEROMETRY

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Abstract

Interstellar scattering can irretrievably blur the images of compact radio sources when examined with extremely high resolution. Because of this effect, diffraction-limited observations of extragalactic sources with an Earth-Moon baseline will only be possible at frequencies above about 7 GHz, in which case the resolution will be $\lesssim 20$ μarcsec. Preliminary observations to determine the potential usefulness of such resolving power are discussed. The simplest of these would consist of a search for interstellar scintillations in compact sources at 10 GHz, which would provide an effective resolution about equal to that of an Earth-Moon baseline at this frequency. Also important in this context is the development of very-long-baseline interferometry (VLBI) in near-Earth orbit, as any ultra-high-resolution observations (such as with an Earth-Moon baseline), if appropriate, would require intermediate baselines for mapping.

Introduction

I wish to address two questions concerning ultra-long-baseline interferometry. First, what are the fundamental limitations imposed by scattering due to irregularities in the interplanetary medium (IPM) and the interstellar medium (ISM)? Second, what, if anything, can be learned in advance about possible source structure on the 10^{-5}-arcsec scales that would be probed using an Earth-Moon interferometer?

Interplanetary and Interstellar Scattering

A fundamental difference between interplanetary scattering (IPS) and interstellar scattering (ISS) should be noted at the outset. At most frequencies ν and solar elongations ε likely to be used (e.g., $\nu > 1$ GHz and $\varepsilon \gtrsim 5°$), IPS is weak. This means that each antenna in the interferometer will undergo an independent time-varying phase shift due to a changing refractive index along each path in the IPM. If the integration time is less than the scintillation time scale, then the fringes are not destroyed (although they would fluctuate in amplitude and phase because of scintillation), and image restoration is possible, in principle. Conversely, ISS is strong for many situations of interest ($\nu \lesssim 10$ GHz at high galactic latitudes and up to considerably higher frequencies at low galactic latitudes). Physically, this roughly corresponds to a different propagation phase shift, not only for each antenna, but also for each part of the source covered by an independent phase blob of size L. The radiation is scattered over an angular distribution $\theta_s \approx \lambda/L$. (See fig 1.) An extragalactic source seen at high galactic latitude, the intrinsic size θ_I of which is in the range

$$L/z \approx (2\ \mu\text{arcsec})\,\nu_1^{1.2} \lesssim \theta_I \lesssim \theta_s \approx (1\ \text{marcsec})\,\nu_1^{-2.2}$$

will have an apparent size $\approx \theta_s$, and its intrinsic structure will be irretrievably lost, even if the integration time and bandwidth are smaller than the time and frequency scales characterizing the scintillation (ref. 1). (In the preceding expression, z is the distance to the scattering "screen," taken to be 250 pc, and ν_1 is in gigahertz.) Of course, the structure of a component smaller in angular size than a phase blob may possibly be recoverable, providing an interferometer having sufficient resolution is used. An Earth-Moon interferometer is capable of resolving structure on scales $< L/z$, at frequencies above 10 GHz (at which level ISS becomes weak at high galactic latitudes, anyway).

Interplanetary Scattering

The degree of decorrelation is determined by the solar elongation and frequency of any particular observation. The locus of parameters for which the decorrelation on an Earth-Moon baseline exceeds 10% is shown in figure 2. The integration time is assumed to be longer than the scintillation time scale, and the scattering is assumed to be weak (which is not strictly true for very small elongation). This assumption is based upon the power spectrum of phase fluctuations measured when the Sun was not in a highly active state (ref. 2). During sunspot maximum, the area of 10% decorrelation and greater may need to be extended by a factor of about 2 (in frequency) above the 90% correlation line shown.

Clearly, IPS does not necessarily present serious problems for such ultra-high-resolution observations at gigahertz frequencies, particularly if small to moderate elongations are avoided. Residual effects caused by this "atmosphere" of the solar system could probably be removed using existing self-calibration techniques.

Interstellar Scattering

The scattering material in the galaxy is distributed in a complex manner, with at least two components (and probably more): (1) a large filling-factor medium with quite large scale height, perhaps 0.5 kpc; and (2) a very low filling-factor medium, consisting perhaps of distinct clumps, and distributed with low scale height (i.e., $\lesssim 100$ pc) (ref. 3). The high-galactic-latitude lines of sight interesting to extragalactic astronomers are typically affected by medium 1 only, and the range of intrinsic sizes blurred by ISS, given previously, was estimated accordingly. Evidently, paths traversing more than one to a few kiloparsecs in the galactic plane intercept one or more type 2 clumps, which result in heavy scattering.

Of particular interest in the context of an Earth-Moon interferometer is the frequency ν^*, above which the scattering size θ_s is smaller than the resolving angle $\theta_R \approx \lambda/B$, where B is the Earth-Moon baseline. This frequency is given in table I for several directions of possible interest. That the full power of the Earth-Moon baseline would be available for extragalactic research at frequencies typically above 7 GHz is shown in table I. It should be noted that because of the inhomogeneity of the scattering medium, even along high-galactic-latitude paths, this estimate will probably vary by about a factor of 2 from one line of sight to the next. Long paths in the plane are so severely affected by scattering that such an interferometer is probably not useful over the radio range for examining distant compact sources near the galactic plane. It is also known that the apparent scattering size fluctuates greatly from one line of sight to the next and, in some cases, is considerably greater than the 50 marcsec given. On the other hand, nearby galactic sources (closer than ≈ 1 kpc) are likely affected to a degree comparable with or even less than extragalactic sources. Hence, such sources could possibly be probed with the full resolution, at sufficiently high frequencies. Of some interest may be burst regions on nearby stars, as discussed by Burns (ref. 4).

Existence of 10^{-5}-Arcsecond Sources

As we have seen, in most situations, ISS limits the usable frequencies to $\gtrsim 7$ GHz, if the full resolving power of the Earth-Moon baseline is to be realized. At these frequencies, $\theta_R < 20$ μarcsec. This immediately raises the question: Are there sources (or components) small enough to show a significant (yet not unresolved) fringe visibility on this baseline? Fortunately, we can probably answer this question before baselines are extended to the Moon. In particular, there are three observational approaches that should be preliminary to the development of an Earth-Moon baseline.

These observational approaches will be described after a brief discussion of this question in the context of known categories of radio sources that may not be hopelessly blurred by the heavy scattering in the galactic disk. Pulsars, if not broadened by scattering, would almost certainly be unresolved even on the Earth-Moon baseline (ref. 5). Active regions on some stars may very well subtend angular sizes ≈ 5 μarcsec at kiloparsec distances and might be profitably studied with the resolution that an Earth-Moon interferometer can provide (ref. 4). In this case, the primary limitation is sensitivity. Of the various types of molecular masers, nearby H_2O masers offer the best prospects for extreme apparent compactness (of the individual spots). Also, H_2O masers in distant galaxies would appear quite small, although, of course, sensitivity is likely to be a problem. Finally, extragalactic continuum sources are thought to be limited to brightness temperatures $< 10^{12}$ K, as a consequence of the incoherent electron-synchrotron emission mechanism. If this limitation applies, as appears to be the case, then 20-μarcsec extragalactic continuum sources would necessarily be fairly weak ($\lesssim 10$ mJy) (ref. 4). The first of three suggested preliminary observational strategies concerns the possibility that weak compact extragalactic sources might require an Earth-Moon baseline to be resolved. In what follows, these observations are discussed.

1. Earth-based VLBI observations of weak (< 100 mJy) compact extragalactic sources — The question to be addressed here is: Why are weak compact sources weak? Is it because they are small in angular size, yet have very high brightness temperatures, close to the Compton limit ($\approx 10^{12}$ K), or because they have lower brightness temperatures and angular sizes perhaps comparable to the well-studied stronger sources? Of course, the answer could lie somewhere between these two explanations. A systematic, high-sensitivity survey of a carefully selected sample, using available Earth-based baselines, could probably shed some light on this question. Of course, it could never tell us whether sources are as small as 20 μarcsec. Nevertheless, a finding that weak sources tend to be smaller or unresolved would be a very interesting result.

2. Development of space VLBI — Several projects have been proposed (e.g., Quasat and the Russian space VLBI project) that would extend baselines into space in the near future. On the longer term, Weiler and his colleagues (ref. 6) have outlined a space-based array with baselines as long as the Astro-Array, or roughly 10^5 km. This is a logical goal for radio interferometry, given our current understanding of compact radio sources. Such an array would provide a good indication as to whether longer baselines, as would be provided by a lunar-based element, are needed. A lunar-based element could then operate as an "outrigger" to the Astro-Array, which would, of course, provide the intermediate baselines required for mapping.

3. Observational search for interstellar scintillation at 10 GHz — Such observations could achieve a resolution equivalent to that of an Earth-Moon baseline, but at negligible "cost." Fast interstellar scintillation is caused by interference in the scattered radiation reaching the observer along various ray paths. The effective resolution afforded by this technique is just the angle subtended by the phase blobs in the ISM; i.e., L/z. Sources smaller than L/z in angular size exhibit fully developed random interference fringes (i.e., scintillations) as observed in pulsars. Sources larger than L/z are resolved and therefore have smaller scintillation "visibility," of approximate magnitude $(L/z)/\theta_1$. Observations of interstellar scintillation would probably not be particularly

useful for mapping intrinsic structure. Nevertheless, these observations would provide a very effective means of detecting ultracompact components.

Thus far, searches for diffractive interstellar scintillation in extragalactic sources have been negative (refs. 7 to 10). Most of these observations, however, were conducted at low frequencies (<0.5 GHz) where L is quite short ($L = \nu_1 \times 10^{4.8}$ km); therefore, any fully scintillating components would have to be extremely compact ($\theta_l < 2$ μarcsec). At higher frequencies, the effective resolving angle increases with L until ν_* is reached, above which the scintillations are weak with scale $L_* \approx \sqrt{\lambda z}$. For typical high-galactic-latitude paths, $\nu_* \approx 10$ GHz. For such lines of sight (to extragalactic sources), the effective resolution just becomes equivalent to that of an Earth-Moon baseline at about 10 GHz! That is, at 10 GHz, $L \approx L_* \approx 6 \times 10^5$ km, and $L/z \approx 15$ μarcsec $\approx \lambda/B$, where $B \approx 4 \times 10^5$ km is the Earth-Moon baseline. Therefore, an extragalactic source compact enough to produce a significant fringe visibility on an Earth-Moon baseline should also exhibit a comparable scintillation "visibility." This premise is indicated schematically in figure 3, which shows the approximate frequency dependence of the interferometric and scintillation visibilities of a 20-μarcsec component.

Clearly, interstellar scintillations should be searched for in compact extragalactic sources at about 10 GHz. At this frequency, the correlation bandwidth of any scintillations will be large, and thus the search will have to be conducted in the time domain (rather than the frequency domain). The expected time scale is approximately $L/(50 \text{ km sec}^{-1}) \approx 3$ hr. It should be noted that Condon and Backer (ref. 7) failed to detect any scintillations in 12 sources at 8.1 and 2.7 GHz. More extensive observations should be conducted, however.

It is widely suspected that the "flicker" reported by Heeschen (refs. 11 and 12) and Simonetti et al. (ref. 13) may be a form of scintillation, quite possibly refractive in origin. This suspicion should be confirmed, however, and its possible utility as a signature of compact structure should be examined.

It may also be possible to apply this technique to fairly nearby radio sources in the galaxy (closer than about 1 kpc). More distant galactic sources would have significant probability of being seen through regions of heavy scattering in the disk, which, if intercepted, would cause the effective resolving angle to be very small. In such a case, the absence of scintillations would not be informative concerning the expected visibility on an Earth-Moon baseline.

Conclusions

If the full resolving power of an Earth-Moon baseline is to be realized, then it must be used at frequencies above 7 GHz (plus or minus a factor of 2), to avoid unrecoverable image degradation due to interstellar scattering. For lines of sight passing through more than about a kiloparsec of the galactic disk, this constraint is much more severe, such that many distant galactic sources would not be observable on this baseline at radiofrequencies.

At 7 GHz, the diffraction-limited resolution of an Earth-Moon interferometer is about 20 μarcsec. Before deploying an interferometer element on the Moon, we should attempt to determine whether any known radio sources have structure on this scale. Fortunately, it is possible to sample "astronomical phase space" at such resolutions ($\approx 10^{-5}$ arcsec) and frequencies (≈ 10 GHz) by searching for interstellar scintillation of compact sources. Such investigations could guide the development of ultra-long-baseline interferometry much as interplanetary scintillation observations provided direct evidence for compact (<1 arcsec) structures in quasars and active galactic nuclei and thus further motivated the development of VLBI.

Should an Earth-Moon baseline be required, then considerable filling-in with intermediate baselines will also be required for mapping. Clearly, the long-term development of radio interferometry in Earth orbit is a reasonable goal (ref. 6), both in terms of usefulness for presently envisioned investigations and in terms of providing a complement to a possible lunar-based element.

I thank Dr. K. Weiler for valuable discussions and Dr. J. Burns for providing a draft of his work on a Moon-Earth radio interferometer in advance of the meeting.

References

1. Cohen, M. H.; and Cronyn, W. M.: Astrophys. J., vol. 192, 1974, p.193.
2. Gapper, G. R.; and Hewish, A.: Mon. Not. R. Astron. Soc., vol. 197, 1981, p. 209.
3. Cordes, J. M.; Ananthakrishnan, S.; and Dennison, B.: Nature, vol. 309, 1984, p. 689.
4. Burns, J. O.: In Lunar Bases and Space Activities of the 21st Century. NASA Lunar and Planetary Institute, 1985.
5. Cordes, J. M.; Weisberg, J. M.; and Boriakoff, V.: Astrophys. J., vol. 268, 1983, p. 370.
6. Weiler, K. W.; Spencer, J. H.; and Johnston, K. J.: NRL Memorandum Report 5657, Naval Research Laboratory (Washington, D.C.), 1985.
7. Condon, J. J.; and Backer, D. C.: Astrophys. J., vol. 197, 1975, p. 31.
8. Armstrong, J. W.; Spangler, S. R.; and Hardee, P. E.: Astron. J., vol. 82, 1977, p. 785.
9. Condon, J. J.; and Dennison, B.: Astrophys. J., vol. 224, 1978, p. 835.
10. Dennison, B.; and Condon, J. J.: Astrophys. J., vol. 246, 1981, p. 91.
11. Heeschen, D. S.: In IAU Symposium 97, Extragalactic Radio Sources, D. S. Heeschen and C. M. Wade, eds., Reidel (Dordrecht), 1982, p. 327.
12. Heeschen, D. S.: Astron. J., vol. 89, 1984, p. 1111.
13. Simonetti, J. H.; Cordes, J. M.; and Heeschen, D. S.: Astrophys. J., vol. 296, 1985, p. 46.

TABLE I.- TYPICAL SCATTERING PARAMETERS

Line of sight	θ_s (1 GHz), arcsec	ν^*, Hz
[a]$\lvert b \rvert > 20^\circ$; extragalactic	1×10^{-3}	7×10^{9}
$\lvert b \rvert < 2^\circ$; distance >5 kpc	50×10^{-3}	300×10^{9}
To galactic center	1	$1 \times 10^{13.8}$

[a] b = galactic latitude.

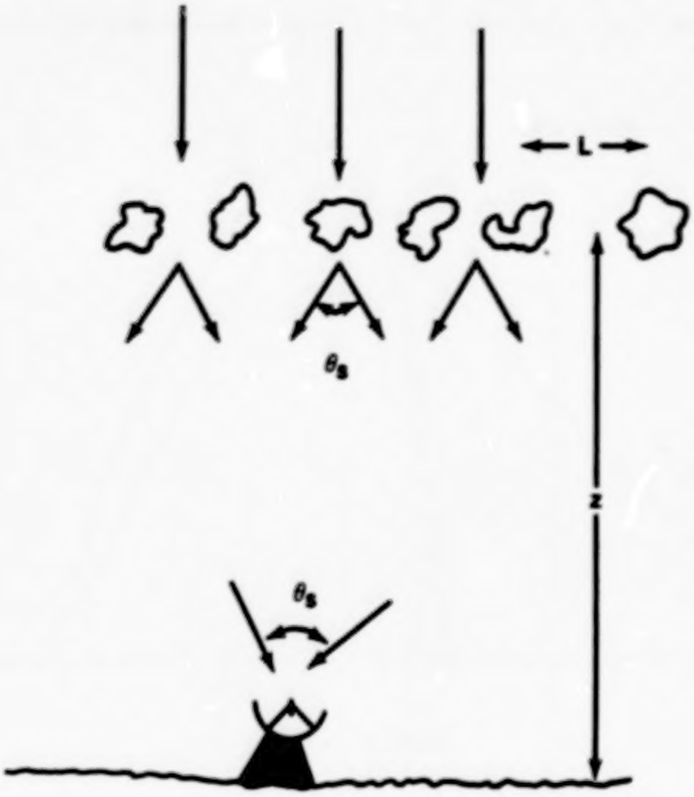

Figure 1.- Geometry of interstellar scattering.

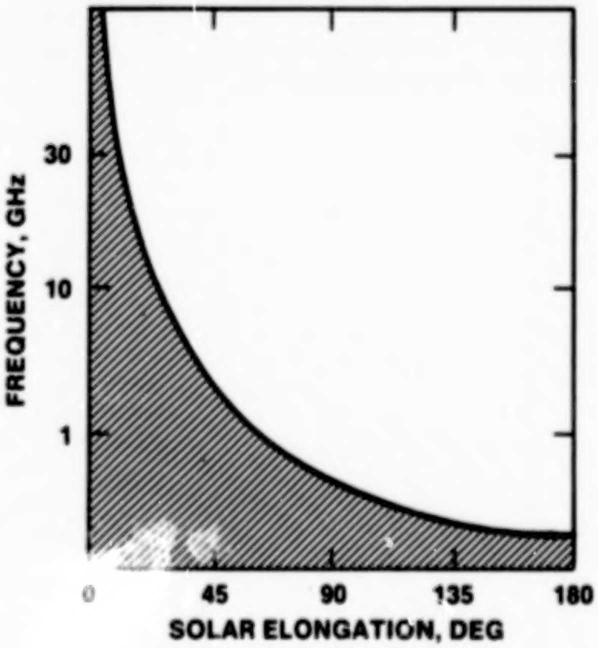

Figure 2.- Parameter space for interplanetary scattering, under typical solar-minimum conditions. If the integration time exceeds the time scale for interplanetary scintillation, observations in the shaded domain will undergo decorrelation of greater than 10%. The assumed baseline is 4 × 10^5 km.

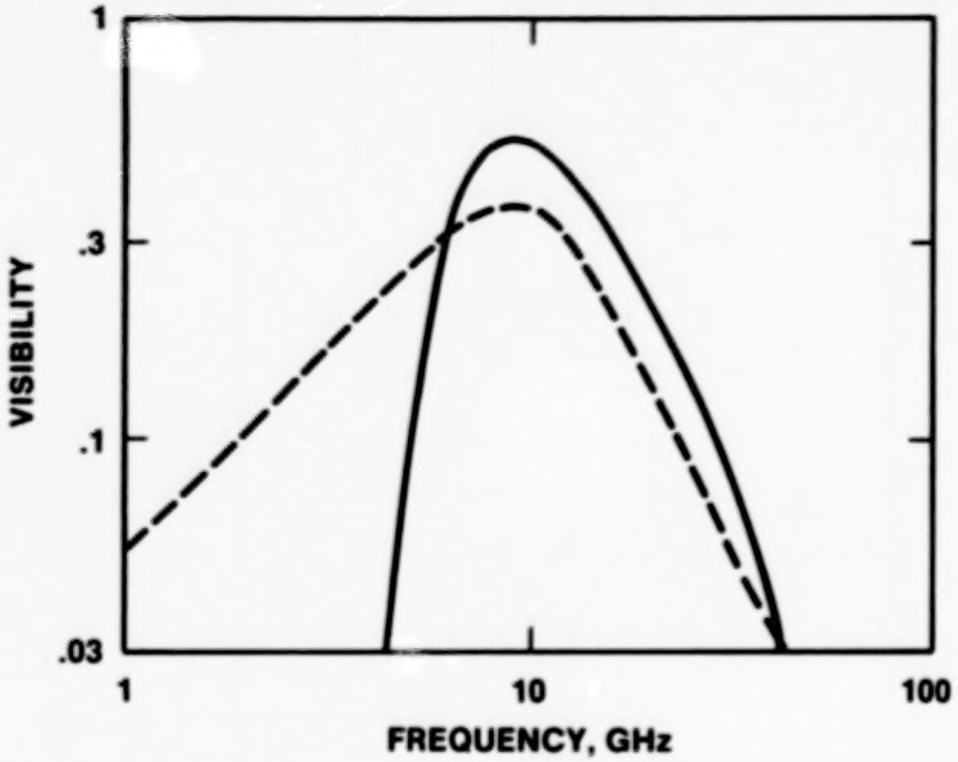

Figure 3.- Schematic illustration of the interferometric (solid line) and scintillation (dashed line) visibilities of a homogeneous 20-μarcsec component. Below a frequency of approximately 7 GHz, the interferometric visibility is reduced because of ISS; above 7 GHz, interferometric visibility is reduced because of overresolution on the assumed baseline of 4 × 10^5 km. The scintillation visibility is reduced at a frequency below approximately 10 GHz because of "overresolution" of the source by the decreasing blob size. (*L* is roughly proportional to ν.) Above 10 GHz, the scintillation is weak and thus the scintillation strength decreases.

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A VERY LOW FREQUENCY RADIO ASTRONOMY OBSERVATORY ON THE MOON*

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Abstract

Because of terrestrial ionospheric absorption, very little is known of the radio sky beyond 10 m wavelength. We propose an extremely simple, low-cost very low frequency radio telescope, consisting of a large (approximately 15 by 30 km) array of short wires laid on the lunar surface, each wire equipped with an amplifier and a digitizer, and connected to a common computer. The telescope could do simultaneous multifrequency observations of much of the visible sky with high resolution in the 10- to 100-m wavelength range, and with lower resolution in the 100- to possibly 1000-m range. It would explore structure and spectra of galactic and extragalactic point sources, objects, and clouds, and would produce detailed quasi-three-dimensional mapping of interstellar matter within several thousand parsecs of the Sun.

Introduction

The spectral window through which ground-based radio astronomers can make observations spans about five decades of wavelength, from a bit less than a millimeter to something more than 10 m. The millimeter cutoff produced by molecular absorption in the Earth's atmosphere is fairly stable, but the long-wavelength cutoff caused by the terrestrial ionosphere is highly variable with sunspot-cycle, annual, and diurnal effects; scintillation on much shorter time scales is also present. Radiofrequency interference imposes further limits, making observations at wavelengths longer than 10 m normally frustrating and frequently impossible.

Consequently, the radio sky at wavelengths longer than 10 m is poorly observed and virtually unknown for wavelengths longer than 30 m, except for a few observations with extremely poor resolution made from satellites. Exploration of the radio sky at wavelengths longer than 30 m must be performed from beyond the Earth's ionosphere, preferably from the far side of the Moon, where physical shielding completes the removal of natural and manmade terrestrial interference that the inverse-square law has already greatly weakened.

The Long-Wavelength Radio Sky

What may we expect in the long-wavelength radio sky (apart from the unexpected, which experience often shows to be more important)?

First, nonthermal radiation from plasma instabilities in solar system objects is present in rich variety, especially from the Sun, Jupiter, Saturn, and Earth itself. This phenomenon was unexpectedly discovered by telescopes flown for other purposes.

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*Reprinted with permission from Lunar Bases and Space Activities of the 21st Century, Lunar and Planetary Institute, Houston, Texas, 1985.

Second, the synchrotron radiation from the galaxy reaches a peak of intensity near a frequency of 4 MHz, or a wavelength λ of 75 m, then drops off as absorption by ionized hydrogen becomes important, and possibly for other reasons as well. This behavior has been seen by the low-resolution (20° beam) telescopes already flown.

Third, the plane of the Milky Way – already dimming at $\lambda = 10$ m – becomes even more absorbed by ionized hydrogen, and many black blots of HII regions are seen in absorption against the bright radiation background. Such clouds, having emission measure that is too small to be noticed optically, would be obvious using a moderate- to high-resolution (1° to 0.1°) very low frequency (VLF) telescope. At longer wavelengths, our distance penetration becomes increasingly limited, decreasing with the square of the wavelength until, by 300 m, unit optical depth corresponds to only a few hundred parsecs.

Fourth, extragalactic discrete sources continue to be visible as wavelength increases (outside the gradually expanding zone of avoidance at low galactic latitudes), and their spectra can be measured, although their angular structure will be increasingly distorted by interstellar and interplanetary scattering. At these wavelengths, it is the expanded halo parts of such objects which are viewed, and inversions will be noted in the spectra of many. For wavelengths longer than about 300 m, HII absorption in our own galaxy will effectively prevent extragalactic observations, even at the galactic poles, and, at wavelengths longer than a kilometer or so, we will be limited to studying objects within a few tens of parsecs of the Sun.

Finally, there may be features of the sky which can be studied for the first time through the use of a high-resolution and high-sensitivity telescope at long wavelengths. These features include

1. Nonthermal emission from stars and planets or other such sources within a few parsecs (if any of these are significantly more powerful than the Sun and the Earth)

2. Radio emission of very steep spectra from new classes of galactic or extragalactic discrete sources that may have gone undetected to date in even the faintest surveys at short wavelengths, yet be detectably strong at 100 m

3. Nearby and compact gas clouds, visible in absorption, the presence of which has hitherto been unsuspected

4. Fine-scale structure in the galactic emission, which – given data at high resolution and multiple low frequencies – can be studied in depth as well as direction

The proposed telescope should provide a uniquely detailed and effectively three-dimensional map of interstellar matter in the galaxy to distances of thousands of parsecs.

The Lunar VLF Observatory

As noted previously, the low-frequency telescopes flown to date have had very poor resolution, although they have been valuable for some studies on very bright sources; e.g., dynamic spectra of the Sun, the Earth, and Jupiter, and the cosmic noise spectrum. Significant advances, however, will require high resolution (say 1°, corresponding to 15 km aperture at 300 m wavelength) and high sensitivity (many elements). A lunar base offers probably the best location in the solar system for constructing an efficient low-cost VLF radio telescope.

In contemplating any lunar-based experiment, the question must first be asked whether it is preferable to perform the work in free space. For the proposed VLF observatory, the Moon offers a number of advantages.

1. It is an excellent platform, capable of holding very large numbers of antenna elements in perfectly stable relative positions over tens or even hundreds of kilometers' separation. (This configuration would be excessively difficult and expensive to achieve in orbit.)

2. The initial telescope can be modest, though still useful, and can be expanded to include thousands of antenna elements added in the course of traverses of lunar terrain undertaken at least in part for other purposes.

3. The dry dielectric lunar regolith permits simply laying the short thin-wire antenna elements on the surface. No structures, difficult to build and maintain, are required.

4. Lunar rotation provides a monthly scan of the sky.

5. The lunar far side is shielded from terrestrial interference, although even the near side offers orders-of-magnitude improvement over Earth orbit because of the inverse-square law, and because of the much smaller solid angle in the sky presented by the Earth.

Limiting Factors

Various natural factors limit the performance of a lunar VLF observatory.

Long-wavelength limits.- The following limits on long wavelengths apply.

1. Interplanetary plasma at a distance of 1 AU has about 5 electrons/cm^3 corresponding to a plasma frequency (f_p) of 20 KHz, or a wavelength of 15 km.

2. The Moon may have an ionosphere of much higher density than that of the solar wind; 10^{-12} torr corresponds to about 40 000 particles/cm^3, if the mean molecular weight is 20. If such an atmosphere were fully singly ionized, f_p would be around 1.8 MHz, usefully but not vastly better than the typical values for the Earth of around 9 MHz. However, ground-based observations of lunar occultations suggest that electron density N_e is actually less than 100 electrons/cm^3. In this case, f_p would be less than 90 KHz (wavelength 4 km), and would set no practical limit to very low frequency lunar radio astronomy. It will clearly be very important for detailed planning of the lunar VLF observatory to have good measures of the lunar mean electron density and its diurnal variations.

Scattering.- Performance limits introduced by scattering and scintillation are as follows.

1. The interstellar medium produces scattering and scintillation, which result in the angular broadening of sources; e.g., the angular size of an extragalactic point source would be about 8 arcsec if observed at 30 m wavelength. The size grows with wavelength to the 2.2 power, becoming 20 arcmin at 300 m.

2. Interplanetary scintillation is more important. Obeying essentially the same wavelength dependence as interstellar scintillation, it ranges from about 50 arcsec at 30 m to a few degrees at 300 m (1 MHz). However, it is still worthwhile to design the telescope with higher resolution than 2° at 1 MHz, since techniques analogous to speckle interferometry may recover resolution down to the limits set by interstellar scintillation, which will be relatively small especially for nearby sources in our galaxy.

Interference.- Natural interference factors limiting performance include the following.

1. Solar: The intensity of the cosmic background radiation is on the order of 10^{-20} W m^{-2} Hz^{-1} sr^{-1}. The Sun is already known to emit bursts stronger than this by an order of magnitude in the VLF range; therefore, the most sensitive observations may have to be performed during lunar night.

2. Terrestrial: Near-side location will always expose the telescope to terrestrial radiations. Consider two known types: auroral kilometric radiation is strong between 100 and 600 kHz; an extremely strong burst would produce flux density at the Moon of about 2×10^{-15} W m^{-2} Hz^{-1} – far stronger than the cosmic noise we are trying to study. Fortunately, it is sporadic and limited to low frequencies. Also, it probably comes from fairly small areas in the auroral zones, so that its angular size as seen from the Moon will be small. Lunar VLF observations below 1 MHz will therefore be limited unless the telescope is highly directive with very low side lobes or built on the lunar far side.

Terrestrial radio transmitters may leak through the ionosphere in the short-wavelength portions of the spectrum of interest. If we assume a 1-MW transmitter on Earth with a 10-kHz bandwidth, the flux density at the Moon would be about 5×10^{-17} W m^{-2} Hz^{-1} without allowing for ionospheric shielding. This would be a serious problem; much weaker transmitters with some ionospheric shielding would merely be an occasional nuisance. Again, this is an argument in favor of a far-side location, particularly for frequencies above 4 MHz or so.

Considerations of Telescope Design

It would be futile to perform a detailed telescope design at this point; however, some general considerations can be addressed.

Frequency range.- The telescope should be broadband, but it should be capable of observing in very narrow bands over the broad range to deal with narrow-band interference. The upper limit of frequency should be around 10 MHz ($\lambda = 30$ m). Even though this wavelength can be observed from the ground, it is extraordinarily difficult to do so. The initial normal lower limit should be about 1 MHz ($\lambda = 300$ m), although the capability for extending observations with reduced resolution to substantially longer wavelengths should be retained.

Resolution.- It is probably useless to attempt resolution at any given frequency better than the limit imposed by interstellar scintillation; e.g., about 20 arcmin at 1 MHz. A reasonable initial target resolution for the observatory might be 1° at 1 MHz. Although this is somewhat better resolution than the limit normally set by interplanetary scintillation, it is probably attainable using restoration procedures. This choice of target resolution implies antenna dimensions of 15 by 15 km for a square filled array, or of 30 by 15 km for a T configuration.

Filling factor.- A 1° beam may be synthesized from a completely filled aperture (100 by 100 elements, for a total of 10^4) or by a T, one arm of which has 200 elements, the other 100, for a total of 300 elements – far less than the completely filled aperture. Many other ways of filling a dilute aperture also exist, including a purely random scattering of elements over the aperture. The filled array has far greater sensitivity, but, what is also important in this context, it has much better dynamic range and a cleaner main beam. This will be of great benefit in mapping the galactic background, particularly in looking at the regions of absorption, which will be of much interest at these frequencies. The sensitivity of the filled array is also decidedly better: a 1° beam produced by a filled aperture at 1 MHz with a bandwidth of 1 kHz and an integration of 1 minute has an rms sensitivity of 1 Jy; the same sensitivity would require an integration of 1 day with the dilute array of 300 elements. The most sensible approach is probably to begin with a dilute aperture and work toward the filled one and thus to increase the power of the system as more antenna elements are set out.

Telescope construction.- The telescope would be an array of many elements. Each element should be thought of as a field sensor, or a very short dipole, rather than as an ordinary beam-forming antenna. The inefficiency of such devices can be great before noise of the succeeding electronics becomes a factor, in view of the high brightness temperature of the cosmic background radiation. An analog-to-digital converter at each element would put the telescope on a digital footing immediately. The exceedingly low power requirement at each antenna element could be met with a tiny solar-powered battery large enough to carry its element through the lunar night.

Communication with the telescope computer at lunar base via radio or perhaps by individual optical-fiber links would bring all elements together for correlation. Bandwidth of the links need only be about 1 kHz per element if only one frequency is to be observed at a time, although maximum bandwidth consistent with economics will produce maximal simultaneous frequency coverage. In any event, the central computer will produce instant images of a large part of the visible hemisphere with the 1° resolution, at one or many frequencies, which can be processed for removal of radiofrequency interference and bursts prior to long integrations for sky maps at various frequencies in the sensitivity range of the system.

Short-wavelength operation.- Operation at the short-wavelength boundary of the telescope range will be a different proposition. Element spacing for 1 MHz is very dilute indeed for 10 MHz; some portion will have to be more densely filled, and operated against the rest of the system as a dilute aperture. At 10 MHz, the system would have a resolution of about 0.1°. In this way, an extremely powerful telescope for work both on extragalactic sources and on galactic structure would result.

Establishing the VLF Observatory

The individual antenna elements – short wires – will probably each weigh about 50 g. Their associated microminiaturized amplifiers, digitizers, transmitters, and solar batteries can all be on several tiny chips in a package of similar weight. Allowing for packaging for shipment to the Moon, the initial array should still weigh less than 50 kg! Materials for the entire filled array would only need about a ton of payload. If individual optical-fiber couplings to the central computer are used, each of these should add only a few tens of grams to the total and thus should not appreciably affect the extraordinarily small cost of transporting the system to the Moon.

Of course, to process the full stream of digital information continuously, a powerful computer is required. Some on-base short-term storage of processed data is probably also desirable, but such data would presumably be dumped back to Earth at frequent intervals. Again, with the increasing miniaturization yet steady growth in power of computer hardware over the next 20 years, the required computer facilities also may be expected to weigh less than a hundred kilograms. It thus seems clear that at least the initial, and quite possibly the ultimate, VLF observatory system could be carried to the Moon as a rather modest part of the first scientific payload.

Laying out the initial system of several hundred antenna elements on the lunar regolith should require only a few days of work with the aid of an upgraded lunar rover having appropriate speed and range. (Such vehicles will be an essential adjunct of any lunar base for exploration, geological and other studies, and general service activities.) The elements need not be placed in accurately predetermined positions, but their actual relative positions need to be known to a precision of about a meter. This determination can easily be made, as the layout proceeds, by surveying with a laser geodometer. The conspicuous tire marks produced by the rover vehicle will delineate the sites of each of the antenna elements for future maintenance or expansion of the system. A concentrated month using two vehicles each carrying teams of perhaps three workers would probably suffice to lay out the full proposed field of 100 by 100 elements.

These estimates, although necessarily rough at this preliminary stage of planning, strongly suggest that because of its extreme simplicity and economy, its almost unique suitability for lunar deployment, and its high scientific promise, the VLF observatory is a major contender for being the initial lunar observatory – perhaps even the first substantial scientific project that should be undertaken from a lunar base.

N89-15826

A LUNAR BASE FOR SETI?

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The proposed NASA search for extraterrestrial intelligence (SETI) will have two search modes.

1. An all-sky survey covering the frequency range from 1 to 10 GHz

2. A high-sensitivity targeted search listening for signals from the ~800 solar-type stars within 80 light-years of the Sun, and covering 1 to 3 GHz

Both modes will use existing antennas: 34-m antennas of the Deep Space Network for the sky survey and large radio astronomy antennas such as the NAIC facility at Arecibo, Puerto Rico, for the targeted search.

The frequency ranges of the search are determined by the microwave window. In free space, this window extends from about 1 GHz to 100 GHz and is limited on the low end by rapidly rising synchrotron radiation from the galaxy and on the high end by quantum noise as shown in figure 1. In the silent valley between these two noises, a third noise source sets the floor at 2.76 K. This is the microwave background – the relict radiation from the big bang.

On Earth, noise is added by the absorption lines of water and oxygen as shown in figure 2. The effect is to raise the floor to about 8 K and to reduce the upper limit of the window to 10 GHz. This reduction is not considered to be serious because there are many reasons for preferring the low end of the window anyway.

The nominal range limit of an SETI system is given by

$$R = \frac{d}{4}\sqrt{\frac{P}{N}}$$

where R = range limit

d = antenna diameter

P = effective isotropic radiated power

N = receiver noise power

We will reduce N as much as possible by using maser or cooled HEMT receivers and by operating in the microwave window. There is nothing we can do about the power P that they radiate. If the proposed search fails, it will be necessary to increase d and hence the antenna collecting area. To do this, one can use

1. Ground-based phased arrays

2. Large shielded antennas in space

3. Lunar arrays

4. Lunar crater Arecibo-type antennas

Let us now consider these alternatives.

1. Ground-based phased arrays

   - Are easily serviced and repaired
   - Can be fairly well shielded from radiofrequency interference (RFI) (except for satellites)
   - Present no unsolved technical problems
   - Are smoothly expandable up to $d > 10^4$ m
   - Are much cheaper than other alternatives (if SETI must bear entire cost)

Therefore, our first conclusion is that SETI does not require a lunar base.

2. Large antennas in space

   - Need only half the area (noise floor is less)
   - Can probably be lightweight
   - Present technological problems of construction, transport, and deployment
   - Must be shielded from RFI
   - Are expandable only in discrete steps
   - Require very expensive maintenance and servicing
   - Require broadband data link

Shielding of the antenna from strong Earth-based RFI is an unresolved, serious problem. The high cost of servicing makes this alternative unattractive. Antennas should be located close to the permanent maintenance base.

3. Lunar arrays

   - Can use larger elements than on Earth because of 1/6g and no wind
   - Require half the area of an Earth-based array
   - Must be on far side
   - Require data link with relay station

4. Lunar crater "Arecibo" arrays (See fig. 3.)

   - Offer possibility of cheaper construction
   - Need many antennas to get full sky coverage
   - Require half the area of Earth-based array

- Must be on far side
- Require data link with relay station

All space alternatives present problems not found in ground-based arrays. The logistics of launch, deployment, and servicing add greatly to the cost. Lunar-based antennas on the far side are probably the most expensive solution of all and are out of the question if SETI must pay the bill. If there is a far-side base for other reasons, the incremental cost of adding SETI might be reasonable.

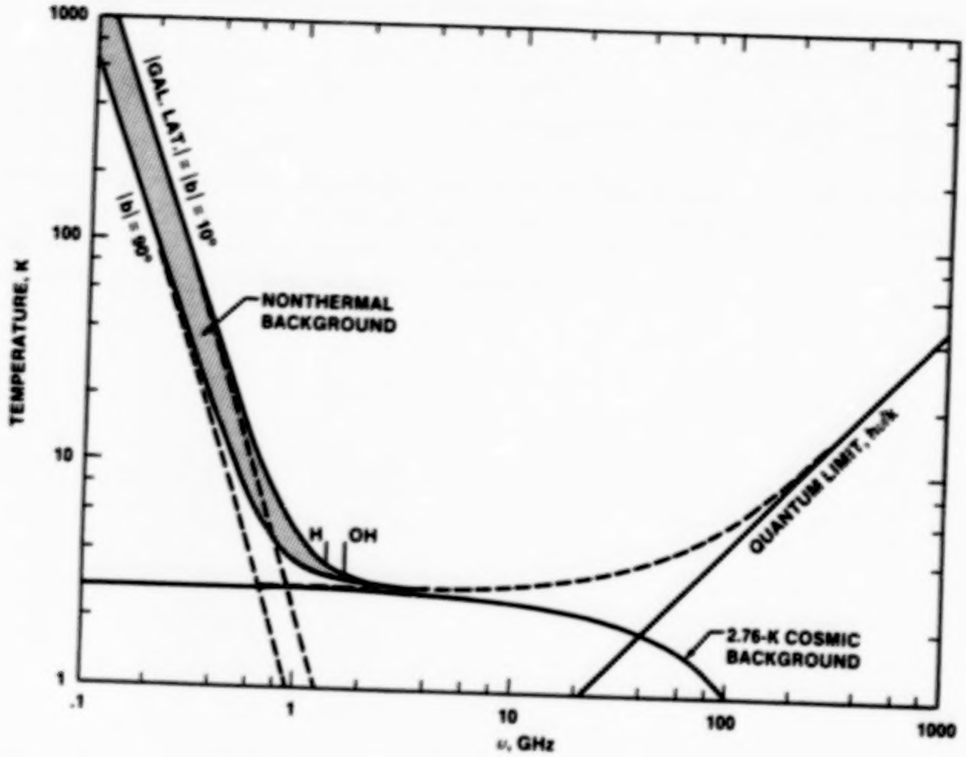

Figure 1.- Free-space microwave window.

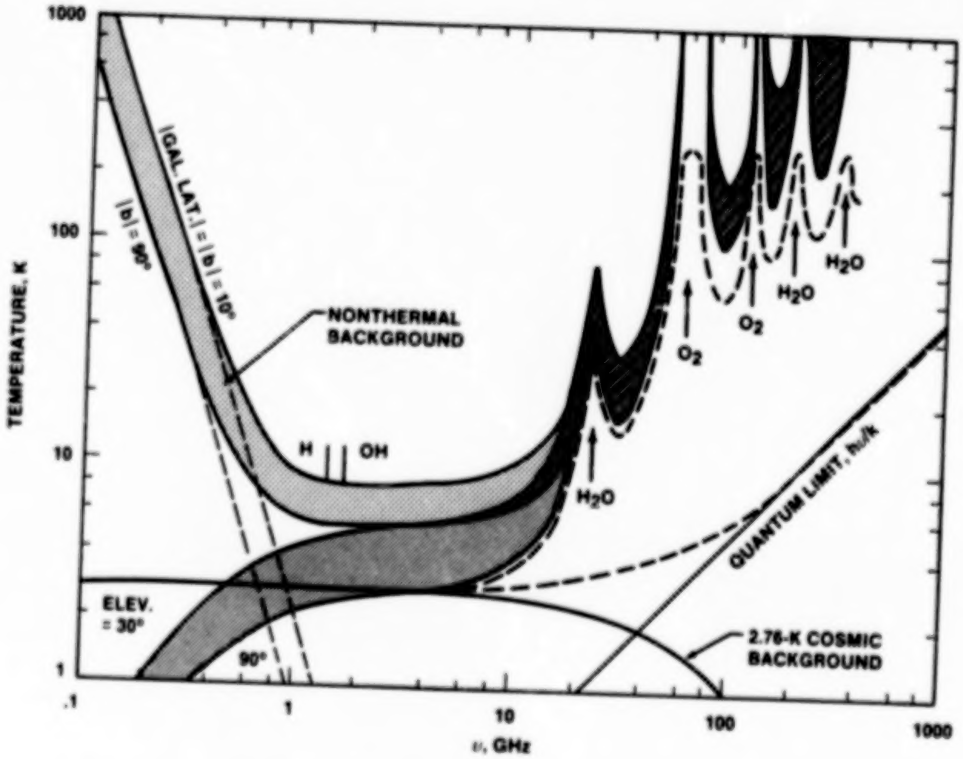

Figure 2.- Terrestrial microwave window.

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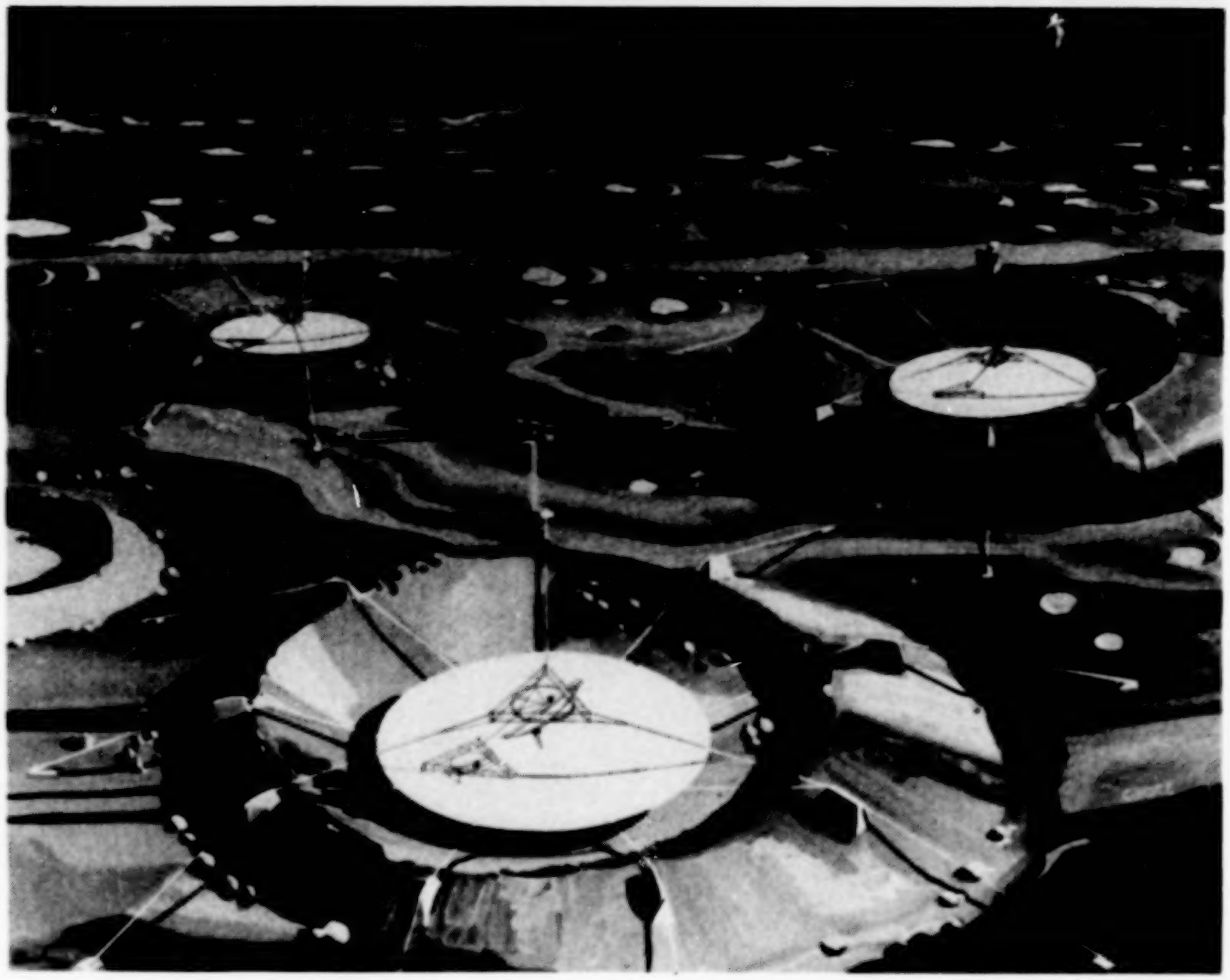

Figure 3.- Artist's concept of an array of three Arecibo-type spherical antennas constructed within natural craters on the far side of the Moon.

PART IV
ENGINEERING CONSIDERATIONS FOR LUNAR BASE OBSERVATORIES

In the final section and paper of these proceedings, the practical aspects of building lunar telescopes are considered from the engineering point of view. S. W. Johnson, a pioneer in lunar facilities designs, discusses the engineering considerations and issues to be resolved in further deliberations on lunar-based observatories. In this paper, the desires of the astronomical community are considered together with the practicality of physical constraints for construction on the lunar surface.

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DESIGN OF LUNAR BASE OBSERVATORIES

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Introduction

In this paper, several recently suggested concepts for conducting astronomy from a lunar base are cited. Then, the process and sequence of events that will be required to design an observatory to be emplaced on the Moon are examined.

Background

In the 21st century, a lunar base will be established which will eventually support astronomical observations from the lunar surface. Several nations and groups of nations will have the capability to advance space colonization beyond Earth orbit. Mankind will return to the Moon, and, when we do, eyes will turn skyward. Man will seek the means to make the best possible use of the characteristics and the environment of the Moon that provide such an excellent platform for astronomical observations.

Observatory Options

Many astronomical observatory concepts and instrument configurations have been suggested for use on the lunar surface. At recent workshops and conferences, the concepts have been discussed in increasing detail (refs. 1 to 4). Additional concepts were suggested and discussed at the NASA-sponsored workshop on Astronomical Observations From a Lunar Base, held in Houston, Texas, in January 1986.

Each observatory concept has its own set of advantages, constraints, and cost drivers. Each requires a different mass of material and effort to be expended on the lunar surface. For each concept, there is an anticipated return in knowledge.

A Moon-Earth radio interferometer (MERI) has been suggested (ref. 2) which could begin with a 10- to 15-m-diameter antenna on the Moon. This antenna, functioning with antennas on Earth and possibly in Earth orbit, would achieve resolution (at the 6-cm wavelength) 30 times better than the proposed Very Long Baseline Array and 10 000 times better than the existing very large array (VLA). Progression would then be to larger or multiple antennas on the Moon.

Another suggested instrument for installation on the lunar surface is a very low frequency (VLF) radio telescope (ref. 3) to investigate the now largely inaccessible radio sky in the 10-m and longer wavelengths. Terrestrial ionospheric absorption prevents terrestrial observations in these wavelengths. This VLF radio telescope would consist of a central computer facility and many short wires, each equipped with an amplifier and a digitizer, laid on the lunar surface over an area of approximately 15 by 30 km.

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Optical interferometers capable of resolution approaching 1 μarcsec may be feasible on the Moon. Burke (ref. 4) suggests a Y-shaped array of twenty-seven 1-m optical telescopes linked to a central correlation station through a set of variable time delays. Each arm of the Y would be 6 km long.

Other concepts proposed include a very large Arecibo-type telescope, sets of instruments for x-ray and gamma-ray astronomy, infrared astronomy, search for extraterrestrial intelligence (SETI), and observations from possible permanently shadowed zones in craters near the lunar poles. Some design considerations for four observatory options follow. For each option, there are common design considerations, such as making use of lunar materials (e.g., for shielding in the near term and for manufacturing composite structural materials in the far term), minimizing mass to be transported from Earth, packaging for transport, and reducing erection complexity.

1. MERI — parabolic dish radio antennas
    a. Site selection and characterization
    b. Thermal strain rates at sunrise and sunset
    c. Sunshield
    d. Foundation excavation and placement
    e. Foundation dynamics
    f. Breakdown into transportable packages with semiautomated erectability
    g. Shielding for electronics and other vital operations
2. VLF radio telescope — wires on surface over a large area
    a. Site selection and characterization
    b. Capability to traverse large area and place wires
    c. Erection and shielding of a control facility
3. Optical interferometer
    a. Site selection and characterization
    b. Control capability (stringent requirements limiting differential settlements, tide compensation)
    c. Location of a suitable site for 6-km-long rails laid out on lunar surface
    d. Dynamic response of lunar rubble to movement of telescopes

4. Arecibo-type radio telescope
    a. Selection of existing crater
    b. Rim-to-floor transportation
    c. Tension and shear-resisting anchors for cables
    d. Foundation elements and support structure
    e. Design for thermal strain compensation

Advantages of the Environment

The features of the lunar environment that are inviting to astronomers are the large, stable platform (with a relatively benign seismic environment), the extremely tenuous atmosphere, the possibility of uninterrupted observations for 14 days, and (on the far side) the avoidance of earthshine and radiofrequency interference of terrestrial origin. Also of significance is the lower acceleration due to gravity (one-sixth terrestrial). There is ample material for shielding and, during the night (and at the lunar poles), an environment advantageous to keeping detectors at their required low temperatures.

The Design Process

Some issues (not in order of importance) to be resolved in the process of designing an astronomical observatory for the lunar surface are type of observatory, operational function of lunar observatory, collectors/sensors/controls, sites and site characterization, observatory/regolith interface, materials for fabrication, positioning/construction, development process, data management system, life-cycle servicing, observatory/infrastructure interface, and shielding. The type of observatory can be selected after enough is known about each proposed concept to be able to quantify the mass required on the Moon, the effort to emplace, and the scientific return. Because the suggested concepts need more development and some effort toward optimizing, quantification is not feasible currently.

When each viable observatory alternative has been brought to sufficient design maturity, it will be evaluated fairly for priority placement on the Moon. The approach to be initiated for each alternative consists of determining expected increase in knowledge, investment cost, and assembly effort; comparing alternatives on the basis of the determinations; and arriving at possible time-phasing for development of each alternative. Questions then to be asked include

1. What is the "right" development sequence for each observatory concept?
2. Given an agreed-to development sequence,
    a. What are the technical requirements?
    b. What are the issues to be resolved?
    c. What are the development steps?

To obtain a fair, unbiased comparative ranking of design solutions for a Moon-based observatory and to identify all alternative solutions, the approach should include the following steps.

1. Perform tradeoff and optimization studies to place each concept in its most competitive position.

2. Be alert to alternative component combinations that yield better design solutions.

3. Identify areas requiring experimental results or technological development.

4. Identify costs and risks associated with each alternative.

The goal is to provide a traceable path to the best design solution for a lunar astronomical observatory and to get an estimate of life-cycle cost. Testing will be done to provide design data, to verify mathematical models for observatory performance, and to investigate critical behavior characteristics. Extensive facilities and resources are required for test and evaluation of space systems (ref. 5). Results of tests will enable verifying designs and identifying problem areas to be corrected. Essential test and evaluation resources must be planned and developed.

The design process for a lunar observatory is shown in figure 1. We are now in "the 'thinking' and gathering of ideas phase" for an astronomical observatory on the Moon.

Twenty years ago, Herbig and others (refs. 6 and 7) suggested the telescope shown in figures 2 and 3 with the portrayed erection sequence. Today, we think in terms of adaptive optics and interferometric arrays. By early in the 21st century, the observatory system design process should arrive at one or more promising concepts from which a "best" solution can be established. A prototype can then be built and tested. Satisfactory design solutions should be ready for emplacement on the Moon by about 2010. Telescopes take a long time to develop. Development of the Hubble Space Telescope has required more than 20 years. Studies should be initiated now to define a lunar-based set of astronomical instruments and experiments for the year 2010. Our knowledge of the Moon from previous expeditions will be very useful in the design process (refs. 8 and 9).

References

1. Duke, M. B.; Mendell, W. W.; and Keaton, P. W., compilers: Report of the Lunar Base Working Group, LALP-84-43. Los Alamos National Laboratory (Los Alamos, N.M.), 1984.

2. Burns, J. O.: A Moon-Earth Radio Interferometer. In Lunar Bases and Space Activities in the 21st Century, W. W. Mendell, ed., Lunar and Planetary Institute (Houston, Tex.), 1985, pp. 293-300.

3. Douglas, J. N.; and Smith, H. J.: A Very Low Frequency Radio Astronomy Observatory on the Moon. In Lunar Bases and Space Activities in the 21st Century, W. W. Mendell, ed., Lunar and Planetary Institute (Houston, Tex.), 1985.

4. Burke, B. F.: Astronomical Interferometry on the Moon. In Lunar Bases and Space Activities in the 21st Century, W. W. Mendell, ed., Lunar and Planetary Institute (Houston, Tex.), 1985, pp. 281-291.

5. Tidd, W. J.; Freyer, E. M.; and Johnson, S. W.: Space and Its impact on Test Resources and Requirements. In Test Ranges and Facilities for the Next Ten Years, International Test and Evaluation Association (Burke, Va.), 1985, pp. 293-306.

6. A Study of Scientific Mission Support of a Lunar Exploration System for Apollo. In Final Report, Vol. III, Scientific Studies, Part 2, SID 65-289-3 (X65-16494), North American Aviation, 1965, pp. 235-243.

7. Scientific Mission Support for Extended Lunar Exploration. In Final Report, Vol. 3, Detailed Technical Report, SID 66-957-3 (N67-34106), North American Aviation, 1966, pp. 273-288.

8. Johnson, S. W.: Siting and Constructing Telescopes and Interferometers on the Moon. Preprint IAF-85-406 of the 36th Congress of the International Astronautical Federation (Stockholm, Sweden), 1985.

9. Johnson, S. W.; and Leonard, R. S.: Design of Lunar-Based Facilities: The Challenge of a Lunar Observatory. In Lunar Bases and Space Activities in the 21st Centry, W. W. Mendell, ed., Lunar and Planetary Institute (Houston, Tex.), 1985.

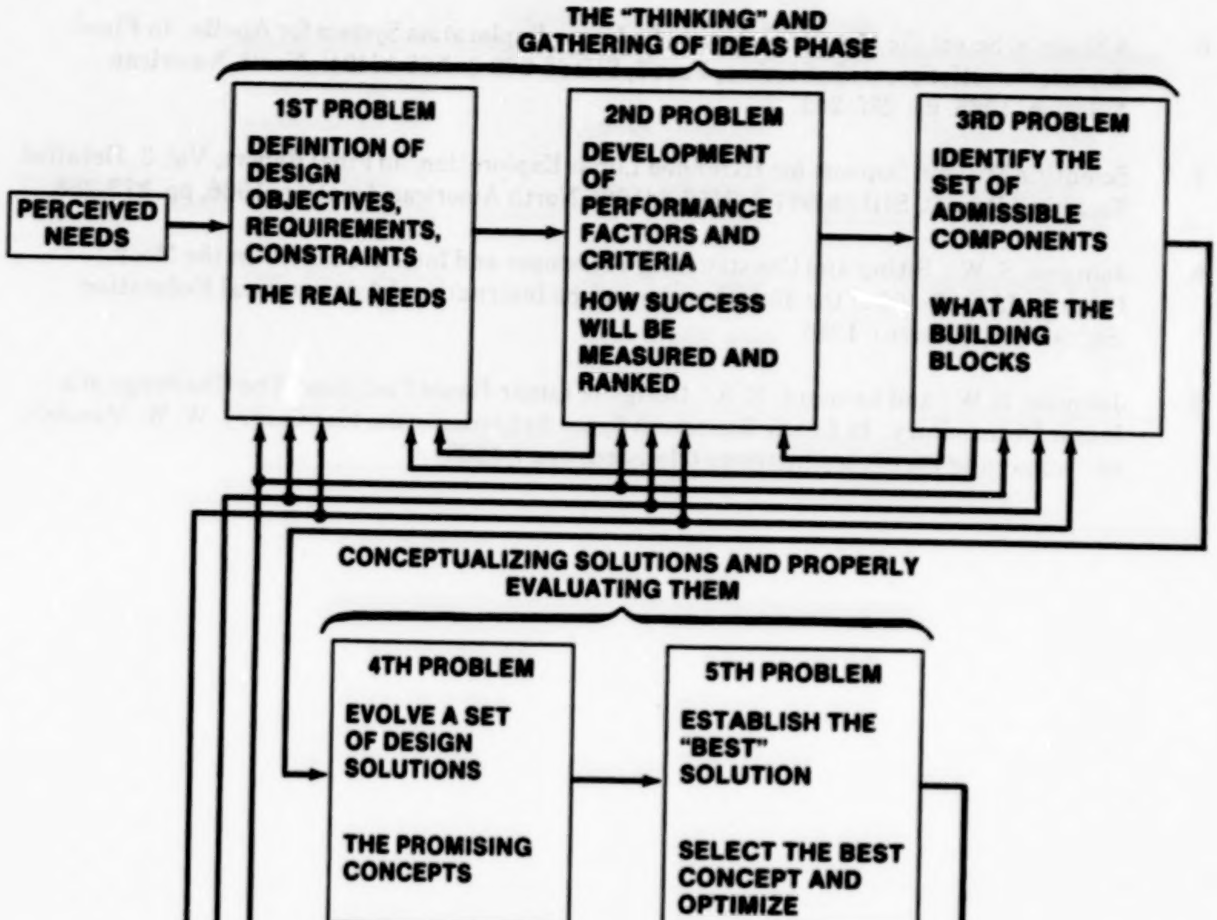
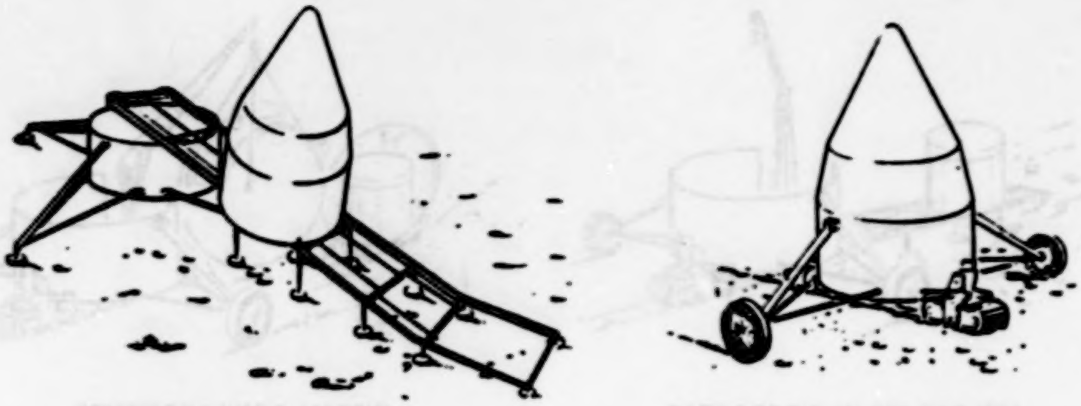
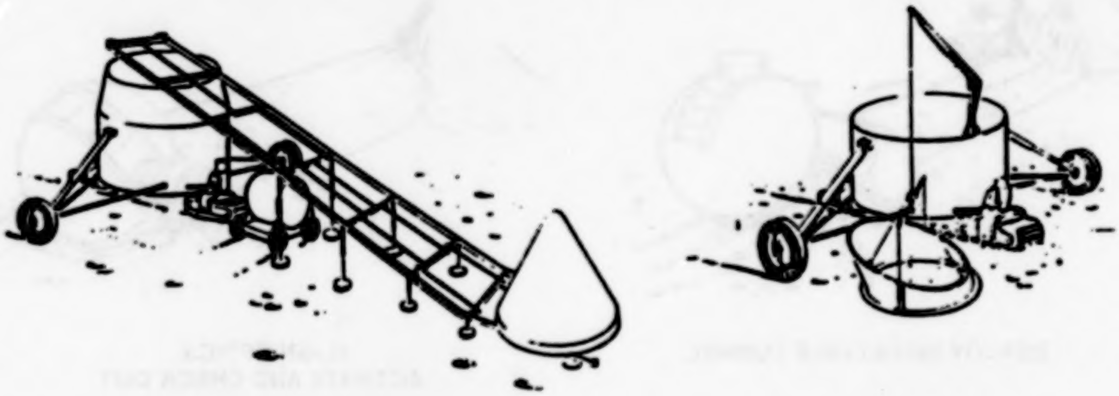

THE "THINKING" AND GATHERING OF IDEAS PHASE
PERCEIVED NEEDS
1ST PROBLEM
DEFINITION OF DESIGN OBJECTIVES, REQUIREMENTS, CONSTRAINTS
THE REAL NEEDS
2ND PROBLEM
DEVELOPMENT OF PERFORMANCE FACTORS AND CRITERIA
HOW SUCCESS WILL BE MEASURED AND RANKED
3RD PROBLEM
IDENTIFY THE SET OF ADMISSIBLE COMPONENTS
WHAT ARE THE BUILDING BLOCKS
CONCEPTUALIZING SOLUTIONS AND PROPERLY EVALUATING THEM
4TH PROBLEM
EVOLVE A SET OF DESIGN SOLUTIONS
THE PROMISING CONCEPTS
5TH PROBLEM
ESTABLISH THE "BEST" SOLUTION
SELECT THE BEST CONCEPT AND OPTIMIZE
TESTING AND VERIFICATION
KNOWING WHEN TO STOP
6TH PROBLEM
BUILD AND TEST A PROTOTYPE
7TH PROBLEM
EVALUATE ANALYSIS AND EXPERIMENTAL RESULTS TO DETERMINE IF
• WORTHWHILE IMPROVEMENTS CAN BE REALIZED
• THE DESIGN IS SATISFACTORY AND READY TO FINALIZE
A SATISFACTORY DESIGN SOLUTION

Figure 1.- The system design process (the seven problems of design).



UNLOAD FROM LUNAR LANDING VEHICLE

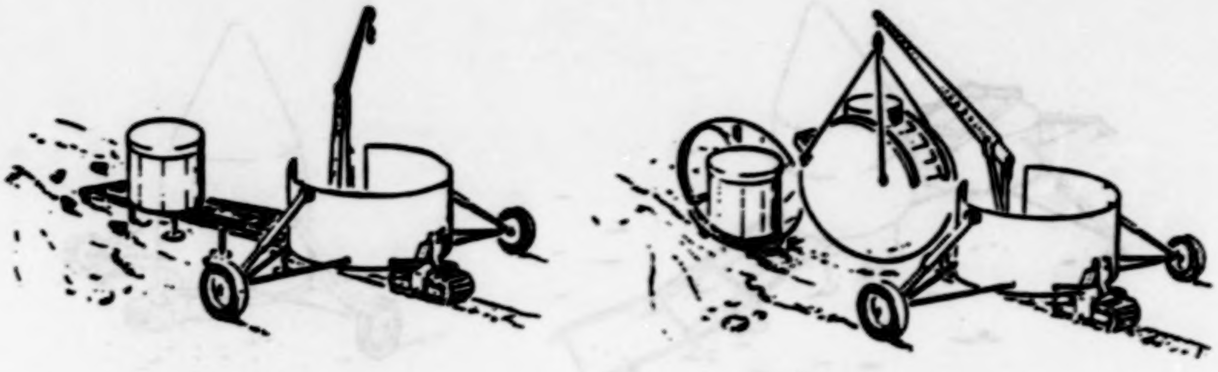
TRANSPORT TO OBSERVATORY SITE



DEPLOY PRIMARY MIRROR SYSTEM AND INSTRUMENT ROOM

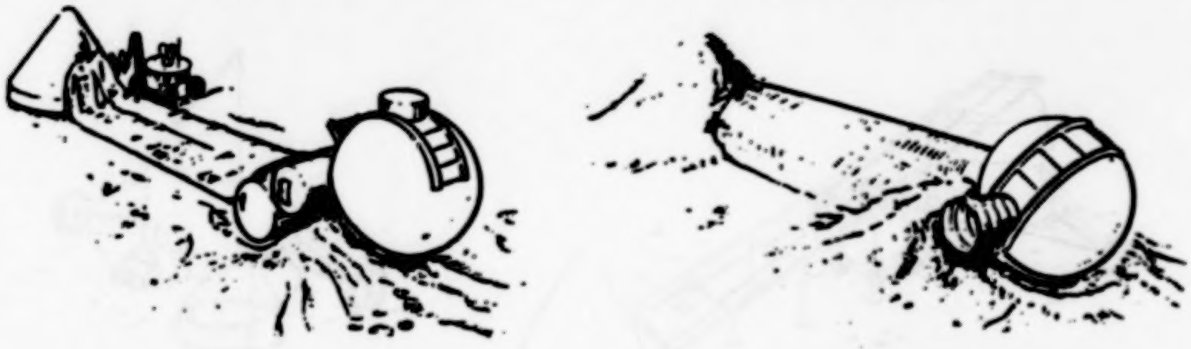
UNLOAD COMPONENTS WITH DAVIT

Figure 2.- Deployment of 100-in. horizontal telescope, part I.



UNLOAD 200-IN. SIDEROSTAT

INSTALL DOME SEGMENTS



DEPLOY INFLATABLE TUNNEL

ALIGN OPTICS;
ACTIVATE AND CHECK OUT

Figure 3.- Deployment of 100-in. horizontal telescope, part II.

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16. Abstract

This document contains papers presented at a workshop held to consider the topic astronomical observations from a lunar base. In part I, the rationale for performing astronomy on the Moon is established and economic factors are considered. Part II includes concepts for individual lunar-based telescopes at the shortest x-ray and gamma-ray wavelengths, for high-energy cosmic rays, and at optical and infrared wavelengths. Lunar radiofrequency telescopes are considered in part III, and engineering considerations for lunar base observatories are discussed in part IV. Throughout, advantages and disadvantages of lunar basing compared to terrestrial and orbital basing of observatories are weighed. The participants concluded that the Moon is very possibly the best location within the inner solar system from which to perform front-line astronomical research.

17. Key Words (Suggested by Author(s))

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Astrometry	Lunar environment
Interferometry	Space platforms
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